Cosmic Distance Ladders

• To determine the velocity-distance law, one needs to measure distances.
  – Determination of distances is one of the most difficult tasks in astronomy.
• In astronomy, we always measure relative distances.
  – E.g., distance to Jupiter = 5.2 AU (relative to Sun-Earth distance)
• Cosmic distance ladders (one is relative to others)
  – Parallax (<10³ light years)
  – Main-sequence fitting (<10⁵ light years)
  – Cepheid stars (<10⁷ light years)
  – Type Ia Supernovae (<10⁹ light years)

Parallax

• Direct method: the most accurate of all.

Distance
= \frac{2\text{AU}}{\theta}

When \theta=2 \text{ arcsec},
Distance
= 3.26 \text{ light years}
= 1 \text{ parsec (pc)}

Main-sequence Fitting

• Measure distances to open clusters relative to the distance to the Hyades open cluster.
  – The distance to the Hyades open cluster (150 light years away) is determined by the direct parallax method.
• Inverse square law
  – Brightness is proportional to \frac{1}{(\text{distance})^2}

Cepheid Stars

• Pulsating variable stars
  – Very bright stars which can be seen at millions of light years away
  – A simple luminosity-period relation
    • The longer the time period between peaks in brightness, the greater the luminosity of Cepheid variable star.
    – Used by Edwin Hubble to determine distances to galaxies.
• Cepheid stars in the Small Magellanic Cloud are used for determining this relation.
  – The distance to the SMC (210,000 light years) is determined by the main-sequence fitting.
Type Ia Supernovae

- Explosion of a white dwarf with a companion star.
- A single type Ia supernova is as bright as the entire galaxy.
  - Supernovae can be seen at billions of light years away!
- Luminosity is approximately the same for all type Ia supernovae.
  - Type Ia supernova is a standard candle.
- How do we know that they are standard candles?
  - Search for type Ia supernovae at distant galaxies with known distances (distances measured by the Cepheid variable stars)
  - Compute and compare luminosities – they are approximately the same.
- Using Type Ia supernovae, we can measure distances up to about redshift of unity, or 10 billion light years away.

Hubble Key Project

- One of the key projects of the Hubble Space Telescope was to accurately determine the velocity-distance relation and the Hubble’s parameter.
  - The HST observed many Cepheid variable stars and obtained distances.
  - Comparing the distances to the measured redshifts, the Hubble’s parameter is obtained.
- Disputes before the HST
  - Alan Sandage and Gustav Tammann
    - $H=50$ kilometers/s/megaparsec
  - Gerard de Vaucouleurs
    - $H=100$ kilometers/s/megaparsec
- The HST Key Project
  - $H=70$ kilometers/s/megaparsec
  - Right in the middle.