Lecture 25: The Cosmic Distance Scale
Sections 25-1, 26-4 and Box 26-1

Key Ideas

The Distance Problem
Geometric Distances
  Trigonometric Parallaxes
Luminosity Distances
  “Standard Candles”
  Spectroscopic Parallaxes
  Cepheid Variables
  RR Lyrae Variables
  Type I supernovae

The Distance Problem
Measuring accurate distances remains the biggest problem in Astronomy
Distances are necessary for estimating
  Total energy released by objects (Luminosity)
  Physical sizes of objects
  Masses of objects
  Distribution of objects in space

Geometric Distances
Direct measurements of distances using geometry

Solar System Distances:
  Orbit Geometry (Copernicus)
  Radar Measurements
Stellar Distances
  Method of Trigonometric Parallax

Method of Trigonometric Parallaxes
Parallax Limits
Ground-based parallaxes are measured to a precision of ~0.01 arcsec
   Good distances out to 100 pc
< 1000 stars this close
Hipparcos parallaxes have a precision of ~0.001 arcsec (at best)
   Good distances out to 1000 pc
   Measured for ~100,000 stars

INDIRECT DISTANCE MEASUREMENTS
One of the most common ways to measure distances without geometry is to assume that you know the luminosity of the object you are observing. Then use the inverse square law that relates brightness and luminosity. We will discuss guessing luminosities by the “standard candle” (“bootstrap”) method below. Other methods of estimating are possible, such as using theoretical models, but they are much less common.

Luminosity Distances
Indirect distance estimate
   Measure the object’s Apparent Brightness, B
   Assume the object’s Luminosity, L
   Solve for the object’s distance, d, by applying the Inverse Square Law of Brightness.

\[ B = \frac{L}{4 \pi d^2} \]

solving for the luminosity distance, \( d_L \)
\[ d_L = \sqrt{\frac{L}{4\pi B}} \]

Standard Candles

Objects whose Luminosity you know ahead of time.

**Bootstrap Method**

“pulling yourself up by your bootstrap” → help yourself, often through improvised means

- Calibrate the Luminosities of nearby objects for which you have a distance (ideally) from Trigonometric Parallaxes

- Identify distant by similar objects, using a distance-independent property that they share (color, pulsation period, spectrum)

- Assume that the distance objects have the same Luminosity as the nearby objects

**Spectroscopic “Parallaxes”**

**Distance-Independent Property:**
- The observed spectrum of the star

**Physics**

- Spectral Type tells you the star’s Temperature
- Luminosity Class tells you which region of the H-R Diagram the star belongs in.

Together, give a unique location on a calibrated H-R Diagram

**Method**

Build a calibrated H-R Diagram for nearby stars with good parallax distances.

Get the Spectral Type & Luminosity Class of the distant star from its spectrum

Locate the star on the calibrated H-R Diagram

Read off the Luminosity and

Compute the Luminosity Distance \((d_L)\) from the measured Apparent Brightness

**NOTE:** has NOTHING to do with “parallaxes”
Spectroscopic Parallax Limits

Distance Limit
- Practical limit is a few 100,000 pc
- Works best for star clusters

Problems
- Luminosity classes are only roughly defined
- H-R diagram location depends on composition
- Faint spectra give poor classifications

Periodic Variable Stars

Stars whose brightness varies regularly with a characteristic, periodic pattern

Distance-Independent Property:
- Period (repetition time) of their cycle of brightness variations

Physics
- Period-Luminosity Relations exist for certain classes of periodic variable stars. On the so-called “instability strip”

Measuring the Period gives the Luminosity
**Period-Luminosity Relationship**

See Figure 25-4

**Cepheid Variables**

Rhythmically Pulsating Supergiant Stars
- Found in young star clusters
- Luminosities of $\sim 10^{3-4}$
- Changes in Brightness: few % to 2-3 times
- Period Range: 1 day to $\sim 50$ days

**Period-Luminosity Relation for Cepheids:**
- Longer Period = Higher Luminosity
- $P=3$ days, $L \sim 10^3 L_{\text{Sun}}$
- $P=30$ days, $L \sim 10^4 L_{\text{Sun}}$

**TYPICAL CEPHEID LIGHT CURVES**
See Figure 21-16

**Cepheid Variable Limitations**
- Found only in young star clusters
- Distance Limit
  - 30-40 Megaparsecs (if you use the Hubble Space Telescope)
  - Crucial for measuring distances to galaxies
- Problems
  - Cepheid parallax measurements at the edge of what is possible (need HST)
  - Two types of Cepheids with different P-L relations ($\delta$ Cephei and W Virginis)
  - Young star clusters often associated with gas/dust

**RR Lyrae Variables**

Pulsating Horizontal Branch (=Low Mass) stars:
- Luminosity of $\sim 50 L_{\text{Sun}}$
- Change in Brightness: factor of $\sim 2-3$
- Period Range: Few hours up to $\sim 1$ day
- Relatives of Cepheid Variables (also on the instability strip)
Period-Luminosity Relation for RR Lyrae

Less strong than for Cepheids

RR Lyrae Star Limitations

Found in old clusters, Galactic bulge & halo

Distance Limit

\(~ 1\text{ Megaparsec if you use Hubble Space Telescope}~

Less luminous than the Cepheids

Limited to our Galaxy, Andromeda and other Local Group Galaxies

Problems

No RR Lyrae stars with good Trigonometric Parallaxes
Less bright than Cepheid stars, so useful only relatively nearby
Period-Luminosity Relation depends on chemical composition

Type I Supernovae

Distance Limit

\(10 \text{ billion light years (3 billion pc)}\)

Disadvantages

Not quite a standard candle
Can be confused with novae and Type II Supernovae
Can be in galaxies with gas and dust
Transient

The Cosmic Distance Scale

No single method will provide distances on all cosmic scales:

Calibrate parallaxes using the astronomical unit
Calibrate H-R diagrams using parallaxes
Calibrate Cepheid and RR Lyrae star distances using H-R diagrams of the clusters that contain them.

Imprecision at each step carries forward, making subsequent steps less precise
This is the challenge of measuring distances.