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

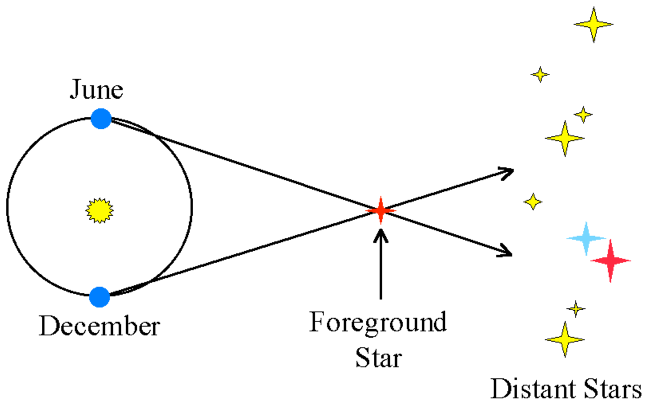
Geometric Distances

<u>Direct</u> 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"

<u>Distance-Independent Property:</u>

The observed spectrum of the star

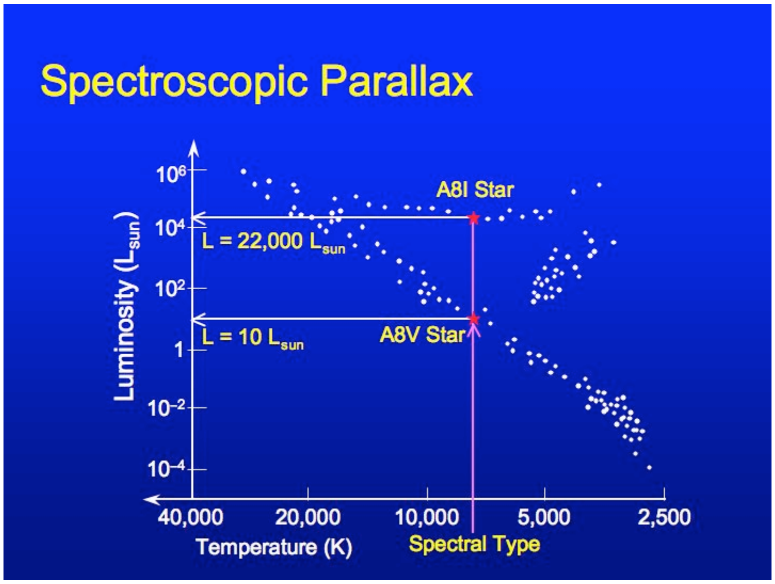
<u>Physics</u>

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

<u>Method</u>

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"



<u>Spectroscopic Parallax Limits</u>

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 patter

<u>Distance-Independent Property:</u>

Period (repetition time) of their cycle of brightness variations

<u>Physics</u>

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 ~10^{3-4}

Changes in Brightness: few % to 2-3 times

Period Range: 1 day to ~50 days

Period-Luminosity Relation for Cepheids:

Longer Period = *Higher* Luminosity

P=3 days, L ~10^3 L_{Sun}

P=30 days, L~10^4 L_{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 (δ Cephei and W Virginis)

Young star clusters often associated with gas/dust

RR Lyrae Variables

Pulsating Horizontal Branch (=Low Mass) stars:

Luminosity of ~50 L_{Sun}

Change in Brightness: factor of ~2-3

Period Range: Few hours up to ~1 day

Relatives of Cepheid Variables (also on the instability strip)

Period-Luminosity Relation for RR Lyrae

Less strong than for Cepheids

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RR Lyrae Star Limitations

Found in old clusters, Galactic bulge & halo

Distance Limit
- ~ 1 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 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.