Distances to Galaxies and the Age of the Universe
The Cosmological Distance Ladder

• No single method or tool can measure distance to all types of objects (planets, stars, galaxies, etc.)

• Use a variety of methods and tools, each one moving farther out and depending on the preceding method
  ➔ “distance ladder”
Tools for measuring distances

• Direct methods for relatively close objects:
  – Radar/Ranging
  – Parallax/Geometry

• Indirect methods:
  – (Brightness – Luminosity) relation: \( B = \frac{L}{4\pi d^2} \)
    • Standard candles
    • Main sequence stars and clusters (use of H-R diagram)
    • Cepheid variables
    • White dwarf supernovae
  – Doppler shifts \( \rightarrow \) Hubble’s Law \( v = H d \)
The cosmological distance ladder from planets in our Solar System out to ~10 billion light-years away.
Tools for measuring distances

• **Direct methods for relatively close objects:**
  – Radar/Ranging
  – Parallax/Geometry

• **Indirect methods:**
  – (Brightness – Luminosity) relation: \( B = \frac{L}{4\pi d^2} \)
    • Standard candles
    • Main sequence stars and clusters (use of H-R diagram)
    • Cepheid variables
    • White dwarf supernovae
  – Doppler shifts \( \rightarrow \) Hubble’s Law \( v = H d \)
Step 1: Radar ranging

Determine size of solar system using radar ranging
Tools for measuring distances

- **Direct methods for relatively close objects:**
  - Radar/Ranging
  - Parallax/Geometry

- **Indirect methods:**
  - (Brightness – Luminosity) relation: \( B = \frac{L}{4\pi d^2} \)
    - Standard candles
    - Main sequence stars and clusters (use of H-R diagram)
    - Cepheid variables
    - White dwarf supernovae
  - Doppler shifts \( \rightarrow \) Hubble’s Law \( v = Hd \)
**Step 2: Parallax**

Determine distances of stars out to a few hundred light-years using **parallax**

Parallax angle $p = 1/2$ total parallax shift each year.

Distance $d = 1/p$ in parsec (= 3.26 light years) with $p$ in arcseconds
Tools for measuring distances

• **Direct methods for relatively close objects**:  
  – Radar/Ranging  
  – Parallax/Geometry

• **Indirect methods**:  
  – *(Brightness – Luminosity) relation*: \( B = \frac{L}{4\pi d^2} \)  
    - Standard candles  
    - Main sequence stars and clusters (use of H-R diagram)  
    - Cepheid variables  
    - White dwarf supernovae  
  – Doppler shifts \( \rightarrow \) Hubble’s Law \( v = H d \)
Relationship between luminosity and apparent brightness

• The inverse-square law for light:

\[
Brightness = \frac{Luminosity}{4\pi \times (distance)^2}
\]

• We can determine a star’s distance if we know its luminosity and can measure its apparent brightness:

\[
Distance = \sqrt{\frac{Luminosity}{4\pi \times Brightness}}
\]

**NEED**: A **standard candle**: an object whose luminosity we can determine without measuring its distance.
Standard candles

A light source of a known, standard luminosity.

Compare luminosity with observed brightness ⇒ get the distance
Distant Standard candles: white dwarf supernovae

Most luminous standard candles and tell us the distances to the most distant galaxies.

• White dwarf supernovae are exploding white dwarf stars that have reached the $1.4 \, M_\odot$ limit

• They all should have nearly the same luminosity $(10^{10} L_\odot)$ because originate from stars of same mass

• Because very bright can be detected in distant galaxies

• Measure their brightness, $+ \, $ luminosity $\rightarrow$ distance
Main-Sequence Fitting

• All main-sequence stars of a particular spectral type have about the same luminosity
• Identify a star cluster that is close enough to determine its distance by parallax and plot on H-R diagram:
  – Brightness + distance $\rightarrow$ luminosity
    
    **Standard: Hydes Cluster**

• Look at far away clusters, measure their brightness, assume same luminosity as counterparts in nearby clusters
  – Luminosity + brightness $\rightarrow$ distance
Main Sequence fitting

For main sequence stars, use their spectral type/color to determine their luminosity.

Brightness + Luminosity

→ distance
Step 3

Apparent brightness of star cluster’s main sequence tells us its distance.

Example: Hyades are 7.5 times as bright as that of Pleiades. So, Pleiades must be \( \frac{7.5}{2.75} = 2.75 \) times as far away.
Discovery of Luminosity-Distance relation in Cepheid variables

• Henrietta Levitt 1912:

  Discovered that the periods of Cepheids are very closely related to their luminosities

  1. period-luminosity relation allows the determination of a Cepheid’s **luminosity**
  2. by measuring its brightness ➔ **distance**

• Hubble then used Cepheids in galaxies to measure their distances
Step 4

Because the period of a Cepheid variable star tells us its luminosity, we can use these stars as standard candles.

Example of measuring the change in brightness of a Cepheid variable, with a period of ~50 days.
Step 4

**Cepheid variable stars**

These regularly change their brightness over days to months.

*The variability period of a Cepheid is related to its luminosity.*
Measured variability period $\rightarrow$ Cepheid’s luminosity.

Luminosity + apparent brightness $\rightarrow$ distance.
Edwin Hubble, using Cepheids as standard candles was the first to measure distances to “spiral nebulae” (other galaxies) in the 1920s.

Hubble still had more to do after this …
Measuring distances to galaxies using Cepheids has been a key mission of the Hubble Space Telescope.
HST’s ultra-sharp vision can see Cepheid variables in galaxies up to 100 million light-years away!

*Cepheid variable in the distant galaxy M100.*
Cepheid in M100 with period of ~1 month
Recall: Standard candles

A light source of a known, standard luminosity

White dwarf supernovae are the most luminous standard candles

They tell us the distances to the most distant galaxies.
Step 5

Apparent brightness of **white-dwarf supernova** tells us the distance to its galaxy.

Can be observed to much greater distance than any other type of star.
The cosmological distance ladder
from planets in our Solar System out
to ~10 billion light-years away.
Cosmic Distance Scale

1 ly
10^3 ly
10^6 ly
10^9 ly

Radar
Parallax
Main-Sequence Cepheids Distant Standards

solar system nearby stars Milky Way nearby galaxies distant galaxies

distant galaxies

How To Use Credits

Copyright © 2008, Pearson Education, Inc.
• http://media.pearsoncmg.com/aw/aw_0media_astro/if/if.html?cosmic_distance_scale
What is Hubble’s Law?
The spectral features of virtually all galaxies are redshifted \( \Rightarrow \) they are all moving away from us.
Hubble’s Law

Edwin Hubble found that a galaxy’s redshift and distance are related (in fact, linearly proportional).

\[ V = H_0 \, d \]
Redshift of a galaxy tells us its distance through Hubble’s Law:

\[ \text{distance} = \frac{\text{velocity}}{H_0} \]

The Hubble Constant
**Hubble’s Law:**

\[(\text{galaxy velocity}) = H_0 \times (\text{galaxy distance})\]
We can measure the speed of a galaxy from its redshift. Hubble’s Law then gives its distance.
What does Hubble’s Law mean?

The Universe is **expanding**!

The Universe had a **beginning**!!!
The Expanding Universe

• Hubble found that more distant galaxies are moving away from us faster (Hubble’s Law). Conclusion: the Universe is expanding!!

• Galaxies are carried along with the expansion.

• Note that galaxies do not perfectly obey Hubble’s Law. Gravity of other nearby galaxies can alter their expected speeds.
Everything is moving away from everything else.

There is no center!

There is no edge!
What is the Universe expanding into?

*Nothing - space itself is expanding!*

Interactive Figure
Cosmological Principle

The universe looks about the same no matter where you are within it.

- There is no preferred place in the Universe (an extension of the “Copernican universe”)
- Matter is evenly distributed on very large scales in the universe.
- No center & no edges
- Not proved but consistent with all observations to date
The Universe had a beginning

\[ \text{time} = \frac{\text{distance}}{\text{speed}} = \frac{1}{H_0} \]

They all started in the same place…
Distances between faraway galaxies change while light travels.

Astronomers think in terms of *lookback time* rather than distance.
Measuring $H_0$ (Hubble’s constant) gives the age of the Universe

13.6 billion years

We can’t see anything older than this: this is the *cosmological horizon*
Cosmological Horizon = the limit of the observable Universe.

The Universe has a finite age of ~14 billion years.

Hence, this is the maximum lookback time and defines how far back in time we can see.