Lecture 12: Distances to stars

Astronomy 111
Why are distances important?

Distances are necessary for estimating:

• Total energy released by an object (Luminosity)

• Masses of objects from orbital motions (Kepler’s third law)

• Physical sizes of objects
Q: What do you do when an object is out of reach of your measuring instruments?
Examples:
• Surveying & mapping
• Architecture
• Any astronomical object

A: You resort to using GEOMETRY.
Method of trigonometric parallaxes

June

December

Foreground Star

Distant Stars
Parallax decreases with distance

*Closer* stars have *larger* parallaxes:

*Distant* stars have *smaller* parallaxes:
**Stellar parallaxes**

All stellar parallaxes are less than 1 arcsecond

Nearest Star, $\alpha$ Centauri, has $p=0.76$-arcsec

Cannot measure parallaxes with naked eye.

First parallax observed in 1837 (Bessel) for the star 61 Cygni.

Use photography or digital imaging today.
Parallax formula

\[ d = \frac{1}{p} \]

\( p \) = parallax angle in arcseconds

\( d \) = distance in “Parsecs”
Parallax Second = Parsec (pc)

Fundamental unit of distance in Astronomy

“A star with a parallax of 1 arcsecond has a distance of 1 Parsec.”

Relation to other units:
1 parsec (pc) is equivalent to
206,265 AU
3.26 Light Years
3.085x10^{13} km
Light year (ly)

Alternative unit of distance

“1 Light Year is the distance traveled by light in one year.”

Relation to other units:

1 light year (ly) is equivalent to

- 0.31 pc
- 63,270 AU

Used mostly by Star Trek, etc.
Examples

\(\alpha\) Centauri has a parallax of \(p=0.76\) arcsec:

\[
d = \frac{1}{p} = \frac{1}{0.76} = 1.3 \text{ pc}
\]

A distant star has a parallax of \(p=0.02\) arcsec:

\[
d = \frac{1}{p} = \frac{1}{0.02} = 50 \text{ pc}
\]
Limitations

If stars are too far away, the parallax can be too small to measure accurately.

The smallest parallax measurable from the ground is about 0.01-arcsec

• Measure distances out to ~100 pc
• But, only a few hundred stars this close
Hipparcos satellite

European Space Agency
Launched in 1989

Designed to measure precision parallaxes to about ±0.001 arcseconds!
• Gets distances good out to 1000 pc
• Measured parallaxes for ~100,000 stars!
Future missions

- **Space Interferometry Mission (SIM)**
  - Launch in about 2013
  - Goal of 4 microarcseconds
    - Direct parallax to any star in our Galaxy
  - Pointed observations of specific targets

- **GAIA**
  - European mission; launch in about 2012
  - Roughly 10-100 microarcseconds precision
  - Measure every star in the Galaxy over roughly 5 years
In-class assignment

- The smallest angle that can be reliably measured for parallax purposes is about 0.01 second of arc. Suppose there are 0.08 stars/pc$^3$ observable near the Sun.
  - How many stars, in principle, exist that could have their distances measured by the parallax method?
  - If accuracy improved to 0.001 second of arc (with Hipparcos, for example), how many stars would have measurable parallaxes?
How “bright” is an object?

• We must define “Brightness” quantitatively.

• Two ways to quantify brightness:
  – *Apparent Brightness*: How bright it looks from a distance.
Luminosity

• *Luminosity* is the total energy output from an object.
  – Measured in Power Units:
    Energy/second emitted by the object (e.g., Watts)
  – *Independent of Distance*

• Important for understanding the energy production of a star.
Apparent brightness

- Measures how bright an object *appears* to be to a distant observer.
- What we measure on earth ("observable")
- Measured in *Flux Units*: Energy/second/area from the source.
- Depends on the *Distance* to the object.
Inverse Square Law of Brightness

The apparent brightness of a source is inversely proportional to the square of its distance:

\[ B \propto \frac{1}{d^2} \]

2-times *Closer* = 4-times *Brighter*

2-times *Farther* = 4-times *Fainter*
Apparent brightness of stars

- **Apparent brightness** is what we measure.

- How bright any given star will appear to us depends upon 2 things:
  - How bright it really is (**Luminosity**)
  - How far away it is (**Distance**).
Appearances can be deceiving...

- Does a star look “bright” because
  - it is intrinsically very luminous?
  - it is intrinsically faint but located nearby?

- To know for sure you must know:
  - the distance to the star, or
  - some other, distance-independent property of the star that clues you in.
Flux-luminosity relationship

Relates apparent brightness \((\text{Flux})\) and intrinsic brightness \((\text{Luminosity})\) through the Inverse Square Law of Brightness:

\[
\text{Flux} = \frac{\text{Luminosity}}{4\pi d^2}
\]
Measuring apparent brightness

• The process of measuring the apparent brightnesses of objects is called **Photometry**.

• Two ways to express apparent brightness:
  – as Stellar Magnitudes
  – as Absolute Fluxes (energy per second per area)
Magnitude system

• Traditional system dating to classical times (Hipparchus of Rhodes, c. 300 BC)
• Rank stars into 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, etc. magnitude.
  – 1\textsuperscript{st} magnitude are brightest stars
  – 2\textsuperscript{nd} magnitude are the next brightest and so on...
• Faintest naked-eye stars are 6\textsuperscript{th} magnitude.
Modern system

• Modern version quantifies magnitudes as:

• 5 steps of magnitude = factor of 100 in Flux.
  – 10\textsuperscript{th} mag star is 100\times fainter than 5\textsuperscript{th} mag
  – 20\textsuperscript{th} mag star is 10,000\times fainter than 10\textsuperscript{th} mag

• Computationally convenient, but somewhat obtuse.
Flux photometry

- Measure the flux of photons from a star using a light-sensitive detector:
  - Photographic Plate
  - Photoelectric Photometer (photomultiplier tube)
  - Solid State Detector (e.g., photodiode or CCD)
- Calibrate the detector by observing a set of “Standard Stars” of known brightness.
Measuring luminosity

• In principle you just combine
  – the *brightness* (flux) measured via photometry
  – the *distance* to the star
• using the *inverse-square law*.

• The biggest problem is finding the distance.
d=1
B=1

d=2
B=1/4

d=3
B=1/9
Summary

• Distance is important but hard to measure
• Trigonometric parallaxes
  – direct geometric method
  – only good for the nearest stars (~500pc)
• Units of distance in Astronomy:
  – Parsec (Parallax second)
  – Light Year
Summary

• **Luminosity** of a star:
  – total energy output
  – independent of distance

• **Apparent brightness** of a star:
  – depends on the distance by the inverse-square law of brightness.
  – measured quantity from photometry.
Binary stars

• **Apparent Binaries**
  – Chance projection of two distinct stars along the line of sight.
  – Often at very different distances.

• **True Binary Stars:**
  – A pair of stars bound by gravity.
  – Orbit each other about their center of mass.
  – Between 20% and 80% of all stars are binaries.
Types of binaries

- **Visual Binary:** Can see both stars & follow their orbits over time.

- **Spectroscopic Binary:** Cannot separate the two stars, but see their orbit motions as Doppler shifts in their spectra.

- **Eclipsing Binary:** Cannot separate stars, but see the total brightness drop when they periodically eclipse each other.
Visual Binary

1890

1940

1990
Center of Mass

- Two stars orbit about their center of mass:

\[ \frac{M_1}{M_2} = \frac{a_2}{a_1} \]

- Measure semi-major axis, \( a \), from projected orbit and the distance.

- Relative positions give: \( M_1 / M_2 = a_2 / a_1 \)
Measuring masses

Newton’s Form of Kepler’s Third Law:

\[ P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \]

- Measure Period, \( P \), by following the orbit.
- Measure semi-major axis, \( a \), and mass Ratio (\( M_1/M_2 \)) from projected orbit.
Problems

• We need to follow the orbits long enough to trace them out in detail.
  – This can take decades.
  – Need to work out the projection on the sky.

• Everything depends critically on the distance:
  – semi-major axis depends on $d$
  – derived mass depends on $d^3$ !!
Spectroscopic binaries

• Most binaries are too far away to see both stars separately.
• But, you can detect their orbital motions by the periodic Doppler shifts of their spectral lines.
  – Determine the orbit period & size from velocities.
Problems

• Cannot see the two stars separately:
  – Semi-major axis must be guessed from orbit
  – Can’t tell how the orbit is tilted on the sky

• Everything depends critically on knowing the distance.
Eclipsing binaries

- Two stars orbiting nearly edge-on.
  - See a periodic drop in brightness as one star eclipses the other.
  - Combine with spectra which measure orbital speeds.
- With the best data, one can find the masses *without* having to know the distance!
Eclipsing binary

Diagram showing the phases of an eclipsing binary system:

1. Brightness graph
2. Time axis
3. Eclipsing phases
4. Orbital motion
Problems

• Eclipsing Binaries are very rare
  – Orbital plane must line up just right
• Measurement of the eclipse light curves complicated by details:
  – Partial eclipses yield less accurate numbers.
  – Atmospheres of the stars soften edges.
  – Close binaries can be tidally distorted.
Stellar masses

• Masses are known for only ~200 stars.
  – Range: ~0.1 to 50 Solar Masses
• Stellar masses can only be measured for binary stars.
Stellar radii

- Very difficult to measure because stars are so far away.
- Methods:
  - Eclipsing binaries (need distance)
  - Interferometry (single stars)
  - Lunar Occultation (single stars)
- Radii are only measured for about 500 stars
Summary

• Types of binary stars
  – Visual
  – Spectroscopic
  – Eclipsing
• Only way to measure stellar masses:
  – Only ~150 stars
• Radii are measured for very few stars.
Questions

• What makes it necessary to launch satellites into space to measure very precise parallax?

• Would it be easier to measure parallax from Jupiter? From Venus?
Questions

• How much does the apparent brightness of stars we see in the sky vary? Why?
• Stars have different colors? So is the amount of light at different wavelengths the same?
• Can we tell the difference between a very luminous star that is far away and an intrinsically low luminosity star that is nearby?
Questions

• What star do we know the mass of very precisely?
• Why is it so unlikely that binaries are in eclipsing systems?
• Most binaries are seen as spectroscopic. Why?
• How can we know the sizes of more stars than masses?