How to Understand Stars
Chapter 17

How do stars differ? Is the Sun typical?

Image of Orion illustrates:

- The huge number of stars
- Colors
- Interstellar gas

How can we describe/classify stars?

- Location
- Temperature
- Luminosity
- Mass
- Evolutionary state
- Physical size
- Composition
- True motion in space
- Environment

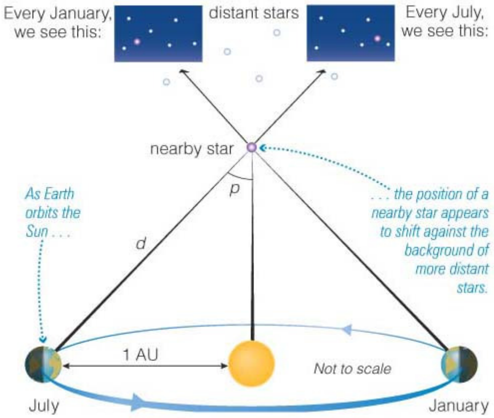
To estimate most parameters, we need to know the distance!

Location in space

Two dimensions are easy – measure angular position from image.

Distance not so easy, the only direct means is by parallax. Other methods later.

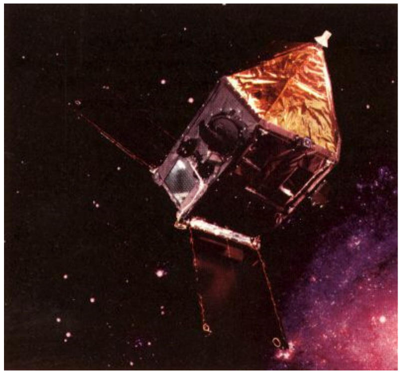
Reminder: parallax is the apparent angular shift of an object due to a change in an observer's point of view. In general, a star will appear to follow an elliptical path over a year.



How parallax relates to distance

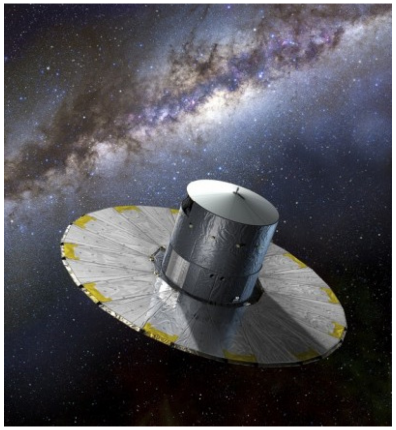
- Remember, a star with a parallax of 1" is 1 parsec ("parallax of one arcsecond") away
- $d\ (pc) = \frac{1}{p('')}$ where *p* is the parallax angle and *d* is the distance.
- Distance units: 1 pc = 3.26 ly = 3.09×10^{16} m = 206,265AU
- First done in 1838.

Limitations



- Until the 1990's we only knew accurate (0.01") parallaxes for a few 100 stars (=> d~100pc)
- In the 1990's the Hipparcos satellite measured over 100,000 parallaxes with an accuracy of 0.001"
- This is still a small portion of the Galaxy

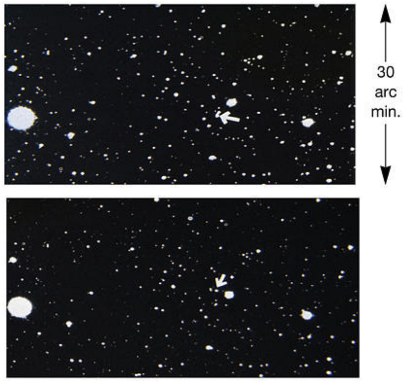
Gaia



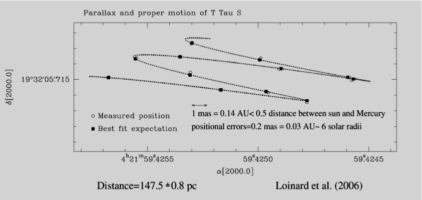
- Launched in 2013 (European). Follow up to Hipparcos, all-sky survey instrument. Aims to measure parallaxes for a billion stars with 20 µas accuracy. Will also measure colors, radial velocities, and (see next slide) proper motions. http://sci.esa.int/gaia/

Proper motion

- Caused by movement of a star relative to the Sun (in contrast to parallax which is an apparent motion of star due to Earth's motion). Hard to measure for distant stars.
- Proper motion is the angle in arcsec a star moves per year
- The superposition of this linear motion and the elliptical motion from the parallax effect leads in general to a helical path on the sky (if both motions can be detected).



Barnard's Star moving 227" over 22 years - a huge proper motion of 10.3"/yr.



Distance=147.5 ±0.8 pc Loinard et al. (2006)

Tangential velocity

$v_t = 4.74\,\mu d$, where μ is proper motion ["/yr], d is distance [pc], and v_t is in units of km/s.

Depends on distance

Radial velocity

Given by Doppler shift:

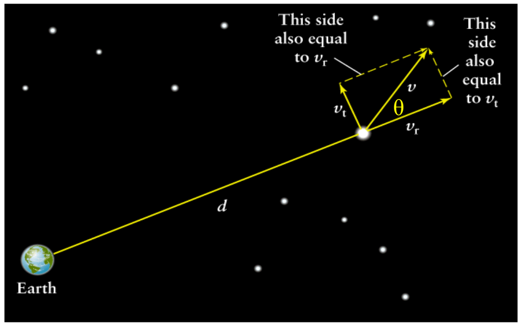
$v_r = [(\lambda_{\text{observed}} - \lambda_{\text{emitted}}) / \lambda_{\text{emitted}}]\ c$

Independent of distance

Space Velocity (relative to the Sun, which is also moving through space)

Speed and direction of star. From Pythagorean theorem

$$V = \sqrt{V_t^2 + V_r^2} = \sqrt{(4.74\,\mu d)^2 + V_r^2}$$



Typical space velocities are 20-100 km/s for nearby stars.

Thus, three quantities need to be measured to get space velocity.

Can also measure direction of motion relative to the line of sight, from $\theta = \arctan(v_t/v_r)$

Why care about stellar motions?

- A tool to learn about stellar properties and structure and dynamics of our Galaxy, even to reveal unseen objects:
  - Motion of the Sun
  - Rotation of the Galactic disk
  - Binary stars – masses of stars
  - Masses of clusters of stars
  - "Stellar streams"
  - Unusual stars

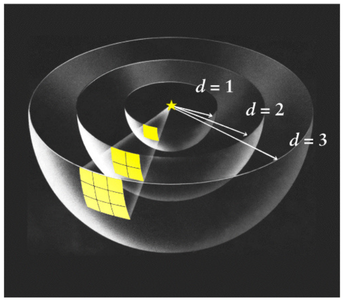
e.g. Stars orbiting an unseen mass at the center of the Milky Way:

http://www.astro.ucla.edu/~ghezgroup/gc/animations.html

Reminder of Luminosity, Incident Flux

- (Box 17.2)
- Luminosity (L, intrinsic property): the total energy output, a physical property of the star. Doesn't depend on distance. Units J/s or W.
- Apparent brightness or incident flux (b, or F_i): measures how bright a star appears to be. Does depend on distance! Units W/m^2.
- The incident flux diminishes as the inverse square of the distance.

$$F_i = L / 4\pi d^2$$



Apparent magnitudes

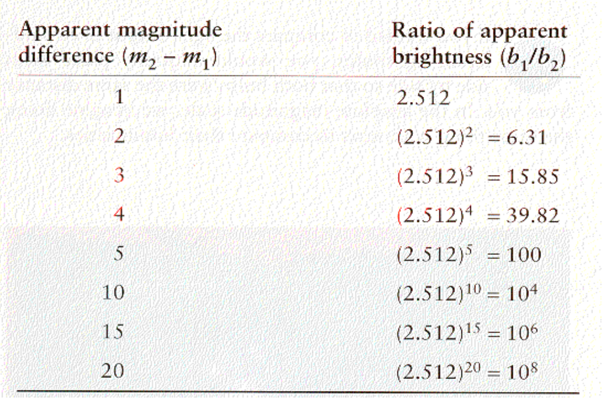
- Logarithmic (base 10) measurement of apparent brightness (incident flux) of stars. Modern scale a refinement of Hipparchus' original scale of magnitudes 1-6. Used mostly in optical astronomy (also near-IR, UV).
- A difference of 5 magnitudes implies a factor of 100 in apparent brightness. Smaller magnitude means brighter star!
- Magnitude difference related to brightness ratio:

$$m_2 - m_1 = 2.5\log\left(\frac{b_1}{b_2}\right)$$

- So if $\frac{b_1}{b_2} = 100$, then $2.5\log\left(\frac{b_1}{b_2}\right) = 5$
- This is a logarithmic and relative scale – zero point arbitrarily chosen.

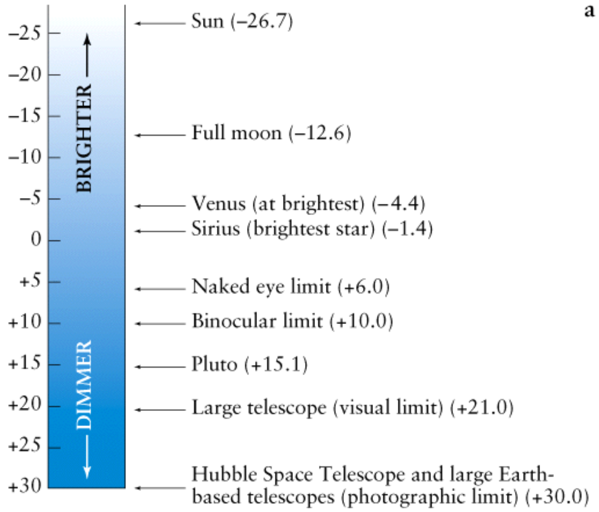
- Or solve for brightness ratio in terms of magnitudes:

$$\frac{b_1}{b_2} = 10^{\frac{m_2 - m_1}{2.5}}$$



Apparent magnitude difference ($m_2 - m_1$)	Ratio of apparent brightness (b_1/b_2)
1	2.512
2	$(2.512)^2 = 6.31$
3	$(2.512)^3 = 15.85$
4	$(2.512)^4 = 39.82$
5	$(2.512)^5 = 100$
10	$(2.512)^{10} = 10^4$
15	$(2.512)^{15} = 10^6$
20	$(2.512)^{20} = 10^8$

The apparent magnitude scale - some examples:



Absolute magnitude

Caution:

Apparent magnitude is NOT luminosity! A star may have bright (small) apparent magnitude because it is close to us, or because its luminosity is high.

We want a brightness scale that takes distance into account and measures luminosity, an intrinsic property of star.

Absolute magnitude:

Definition: the apparent magnitude a star would have if it were precisely 10 pc away from us. Call this *M*. Then, for two stars with luminosities L_1 and L_2, the difference in their apparent magnitudes at 10 pc would depend only on the ratio of their luminosities:

$$M_2 - M_1 = 2.5\log(\frac{L_1}{L_2})$$

Zero point again arbitrarily chosen. Examples:

M	Star
-5.6	Betelgeuse
1.3	Sirius A
+4.7	Sun
+8.6	Sirius B

Given this definition, the inverse square law is expressed in magnitudes by:

$$m - M = 5\log(d) - 5$$

m is apparent magnitude (measured)
d is distance in pc
M is absolute magnitude

Distance modulus

- Instead of giving an object's distance, we sometimes speak of its “distance modulus” *m - M*

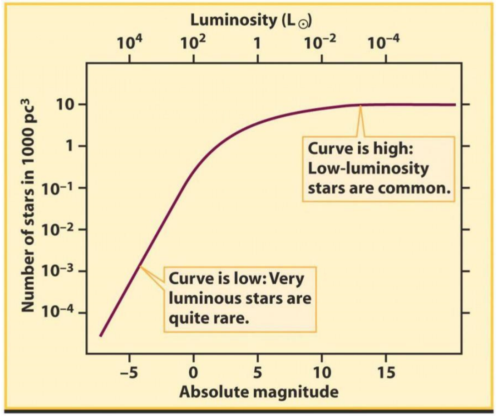
$$m - M = 5\log(d) - 5$$

m – M	Distance
0	10 pc
10	1000 pc
15	10,000 pc

Note these magnitudes do not refer to any wavelength or color. But it is in practice difficult to measure a star’s light over entire spectrum. Typically observed through a filter that lets in, e.g., blue, red, infrared, UV, etc. light.

Luminosity function

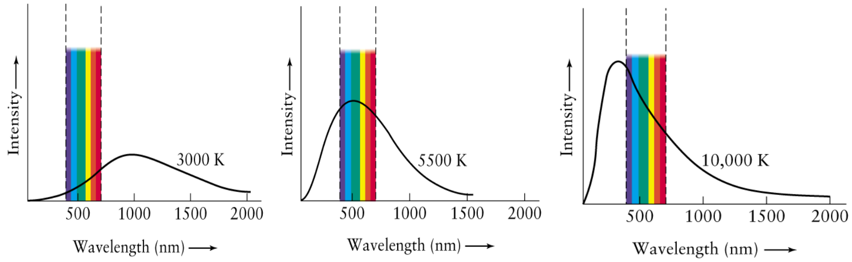
- A function you can examine once you have distances to many stars
- Describes the relative numbers of stars with different luminosities
- Note the enormous range in luminosity
- There are more faint stars than bright. Why?



Determined in Solar neighborhood

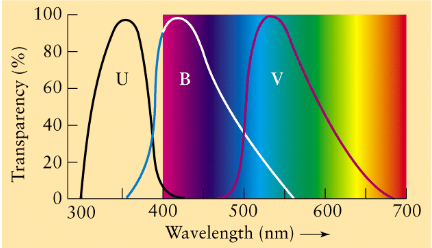
Colors and temperatures of stars

- *Reminder:* from Wien's law $\lambda_{max} = 0.0029 / T$ (units: m, K) we expect hotter objects to be bluer.

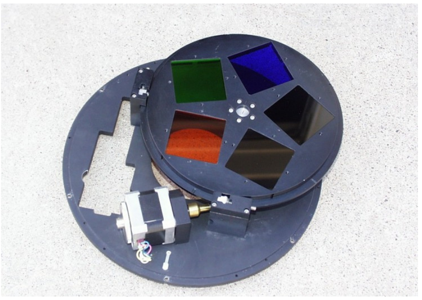


To measure colors

- A set of filters can be used to determine the colors of stars



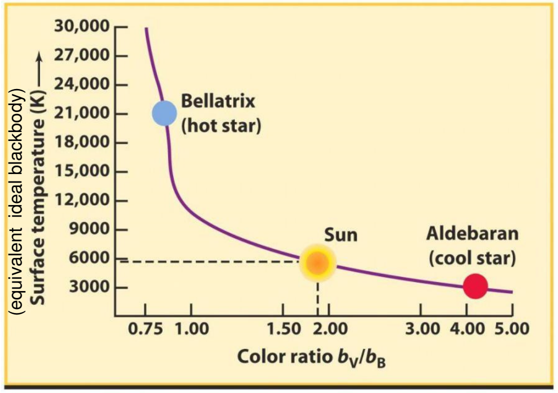
The Johnson UBV system



- Determine relative brightness in, e.g., B and V filters: b_V/b_B. (Usually put on magnitude scale, i.e. $m_B - m_V$, but don't worry for this class).

- Note we don't need distances

Temperature, color and color ratio



- The b_V/b_B color ratio is small for hot stars, and large for cool stars.