PROPERTIES of STARS: I
Distances and Luminosities
pages 307 - 313

DISTANCES to the STARS

- Wide variety techniques to measure distances.
- With increasing distance, each technique relies on measurements of nearer objects.
- An error at one step translates through all subsequent steps.
- “Nearby” objects → “Most distant” is a sequence of decreasing accuracy.

Astronomical Distance Pyramid

18.1 Methods of Distance Measurement

a

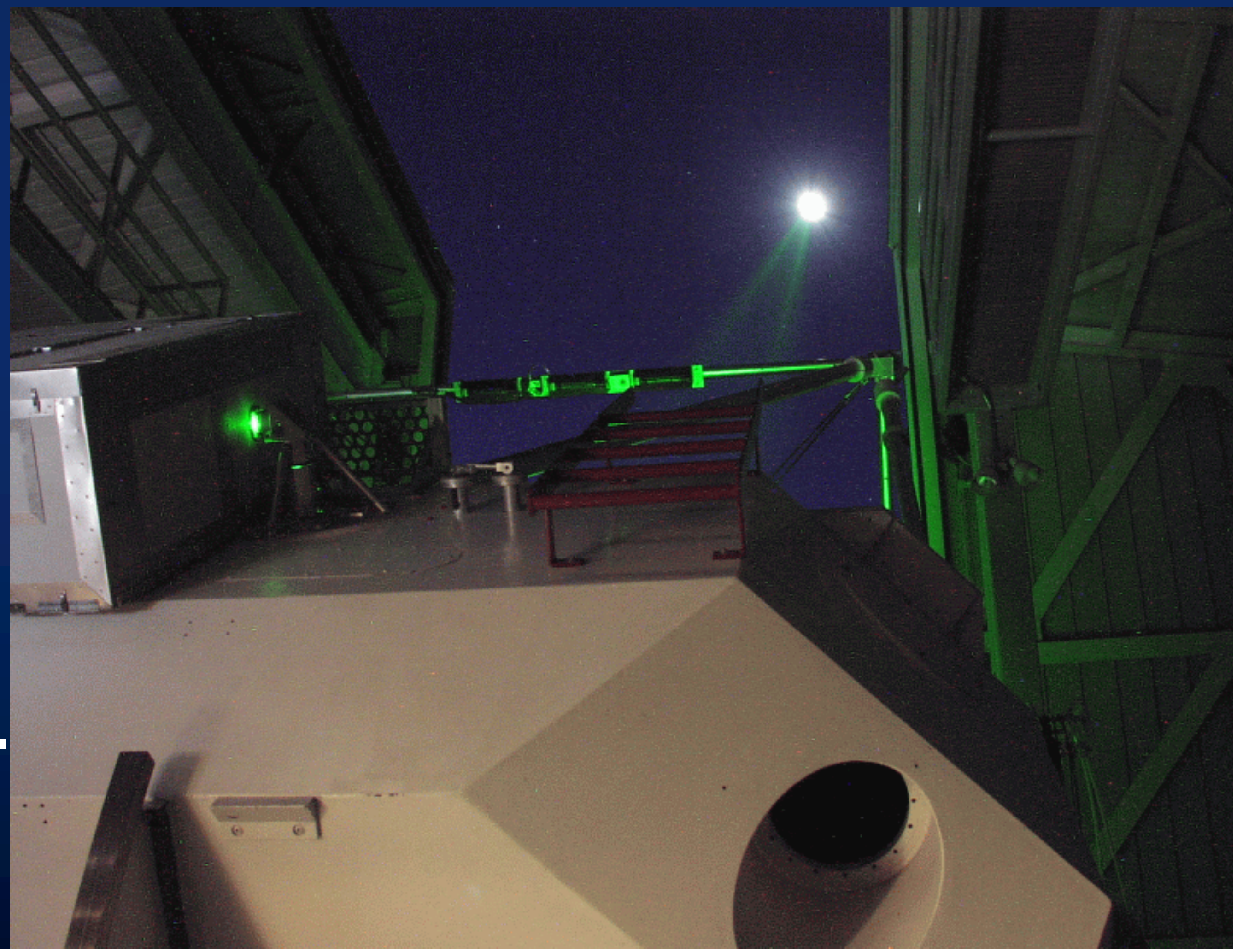
10	Expansion of Universe (Hubble's law)	*5000 Mpc*
9	Brightest galaxies in clusters of galaxies	*2000 Mpc*
8	Luminosities of galaxies	*100 Mpc*
7	Brightest stars in galaxies, size of HII regions	*10 Mpc*
6	Period–luminosity relation for cepheids	*4 Mpc*
5	Colour–magnitude diagrams of star clusters (main sequence fitting)	*30 000 pc*
4	Dynamical parallaxes of moving clusters of stars	*300 pc*
3	Triangulation from different sides of the orbit of Earth (stellar parallaxes)	*30 pc*
2	Periods of planetary orbits (Kepler's third law)	*1/3000 pc*
1	Triangulation from Earth (parallax of Sun or minor planet), nowadays radar	*1/15 000 pc*

Distances Inside Solar System

Laser distance to Moon, radar distance to Venus.

Accuracy of a few cm (10^{-8} % for Moon).

Radar timing to Venus gives accurate distance to Sun.



Some Laser Ranging Facts

US Apollo manned missions to Moon left arrays of mirrors on Moon (late '60s - '70s)

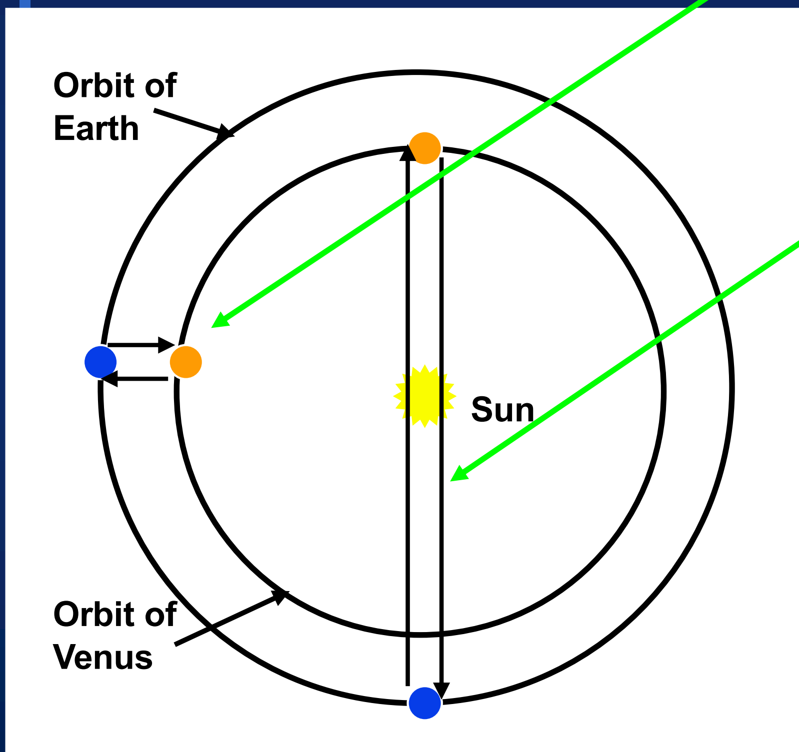
Like highway signposts

Aiming to hit one of these like hitting dime With rifle from distance ~1 km

Echo signal weak - only 1 in 10^{18} photons sent is detected

Proof astronauts actually landed on the Moon

Distances inside Solar System: Distance to the Sun



Closest approach of E and V

Most distant E and V

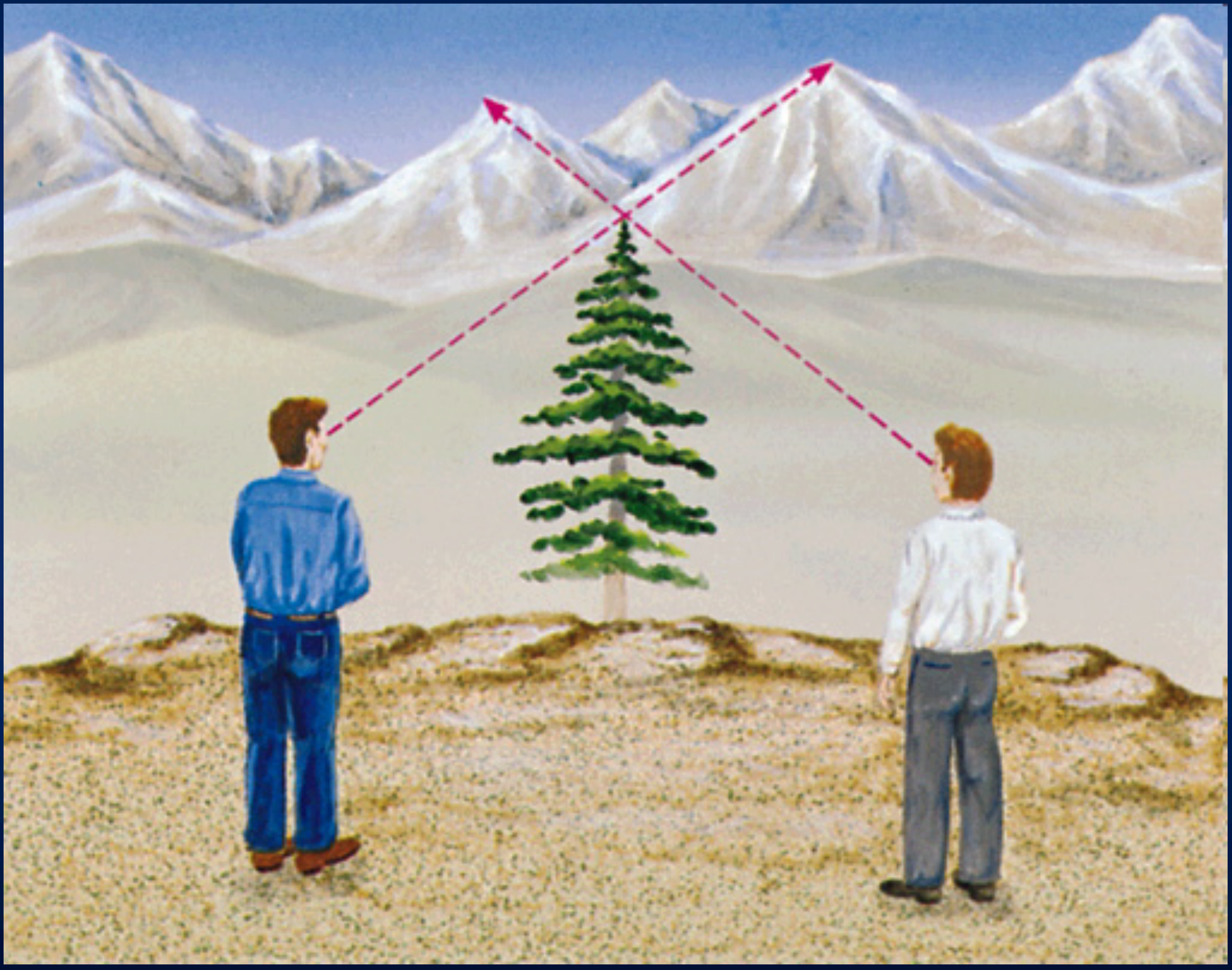
Time radar **returns**

$(T_{distant} + T_{nearest}) \times c / 4 =$ Earth-Sun distance

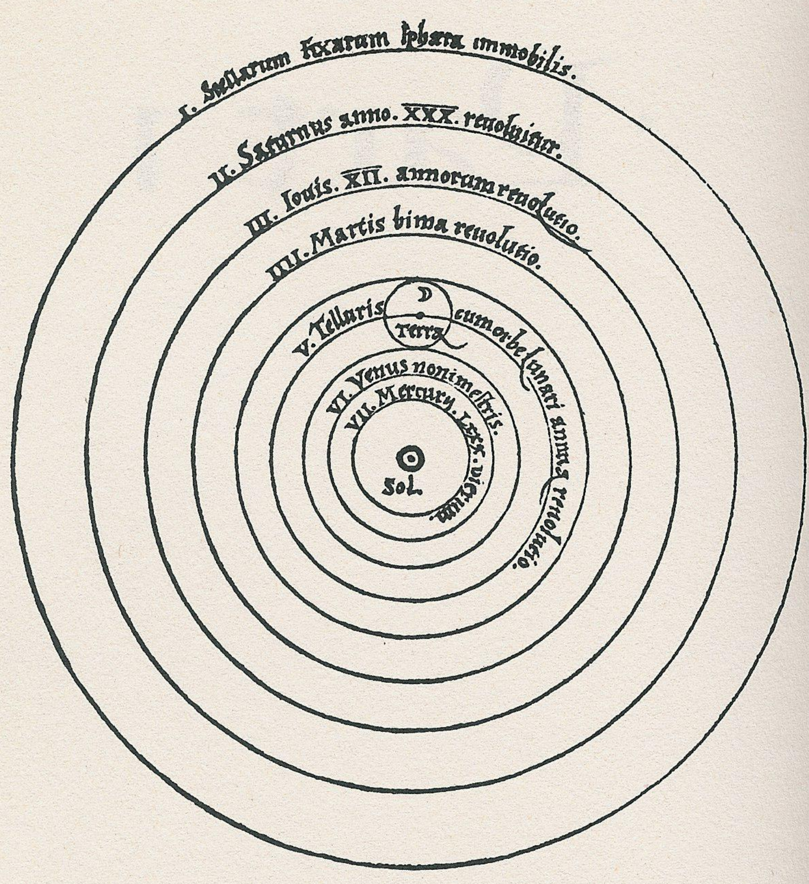
1 Astronomical Unit (AU) = 1.49597870×10^8 km

accuracy of about 100 m

PARALLAX



PARALLAX

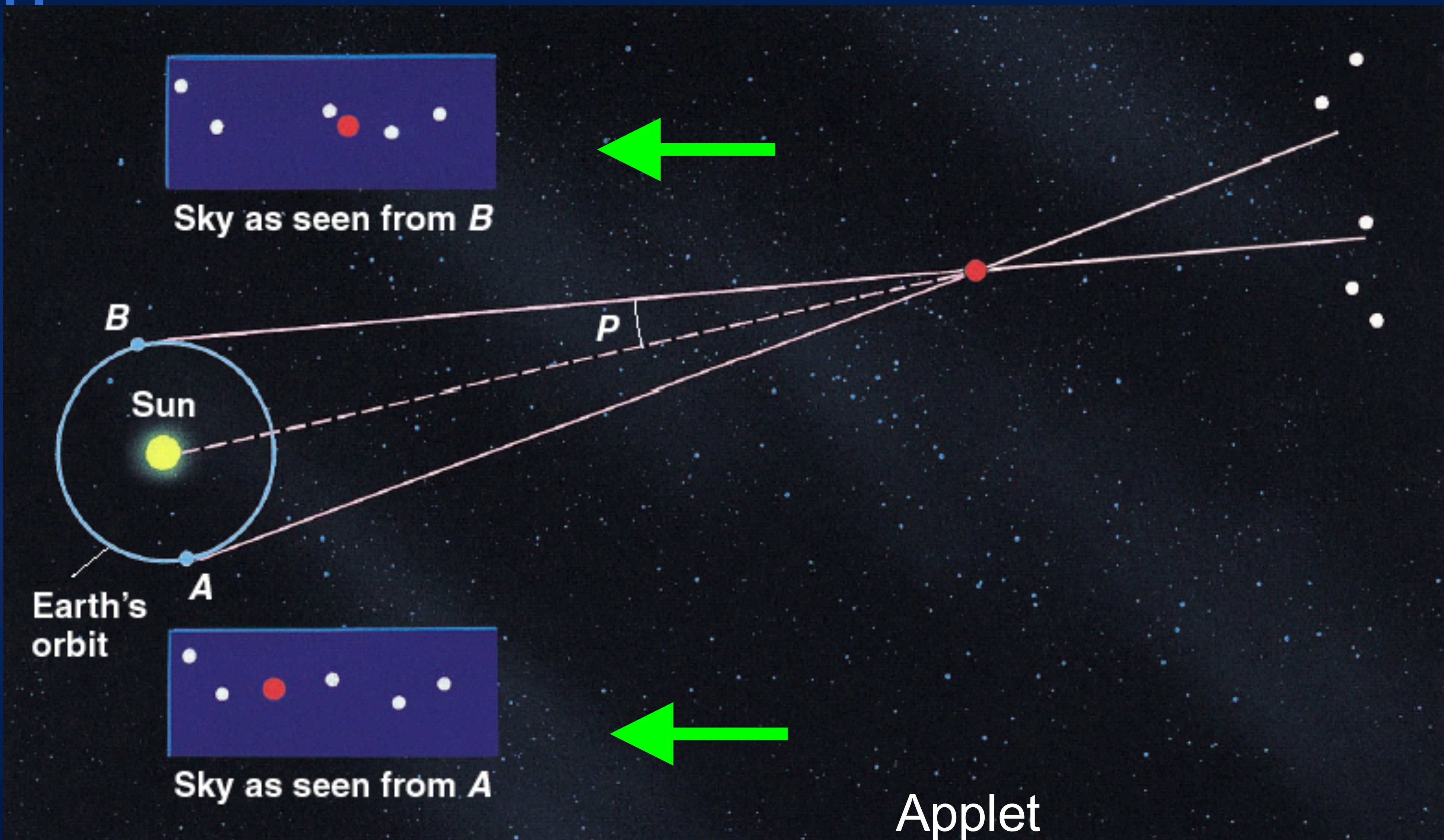


The Sun-centered model of the cosmos. From Copernicus, *De Revolutionibus*, 1543.
Source: *Wolbach Library, Harvard University.*

With a Sun-centered Solar System and a moving Earth, objects outside the Solar System can potentially exhibit parallax. Whether we can measure it will depend on their distance.

Tycho Brahe looked for parallax of the stars in the 1570's as proof of the Copernican Theory. Did not see it - concluded that Earth did not move. Measurement accuracy 1' whereas the parallax of nearest star < 1".

STELLAR PARALLAX



Applet

STELLAR PARALLAX

Only direct way of getting distances to stars

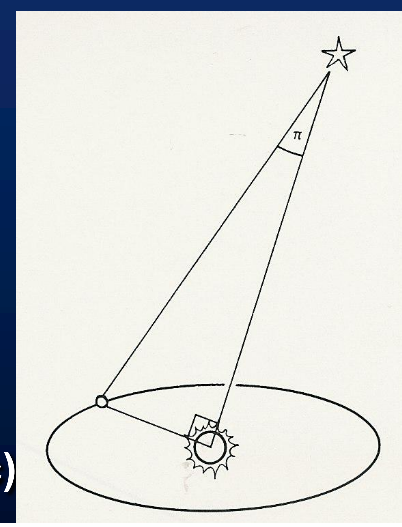
Smaller the parallax, farther is star

Over year star, describes ellipse on sky (special cases: circle at pole, line if in ecliptic) - semi major axis is parallax (π)

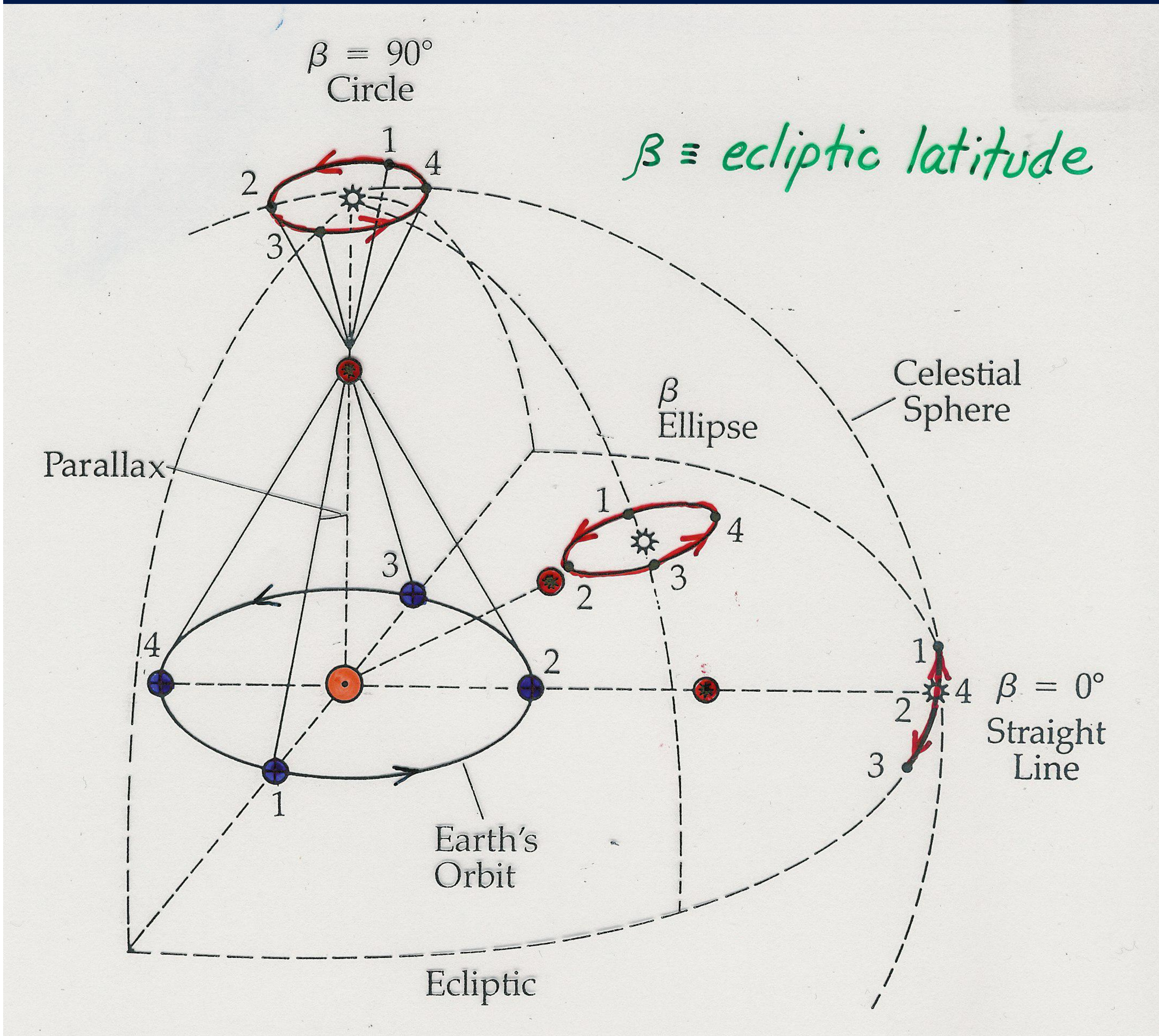
Unit of distance is parsec (pc) defined so that at 1 pc star subtends angle 1” on E-S baseline

From small angle formula:
1” = 1 AU / 1 pc
→ 1/206265 = 1AU / 1parsec
→ 1 pc = 206265 AU = 3 x 10^{13} km

D = 1/π, π in “, D in pc;
nearest star: π = 0.762”, 1.31 pc (limit 2-300 pc)



Parallax and position



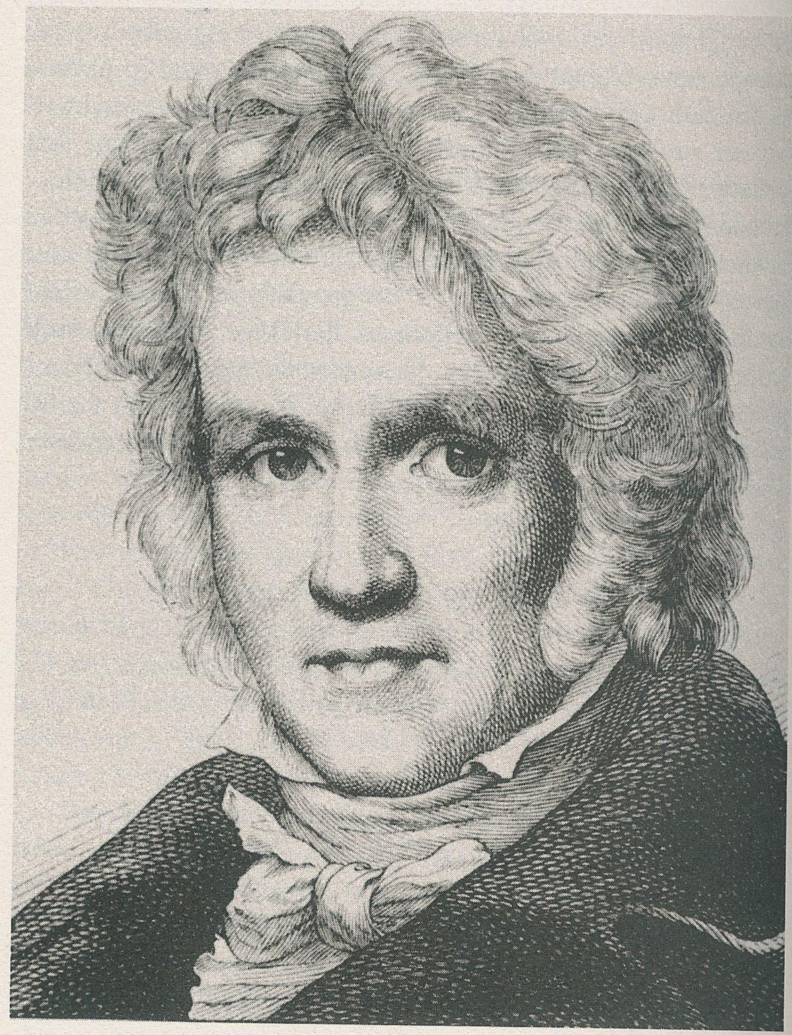
Position of star determines the parallax effect

Bessel Measures Stellar π 1838!

61 Cygni

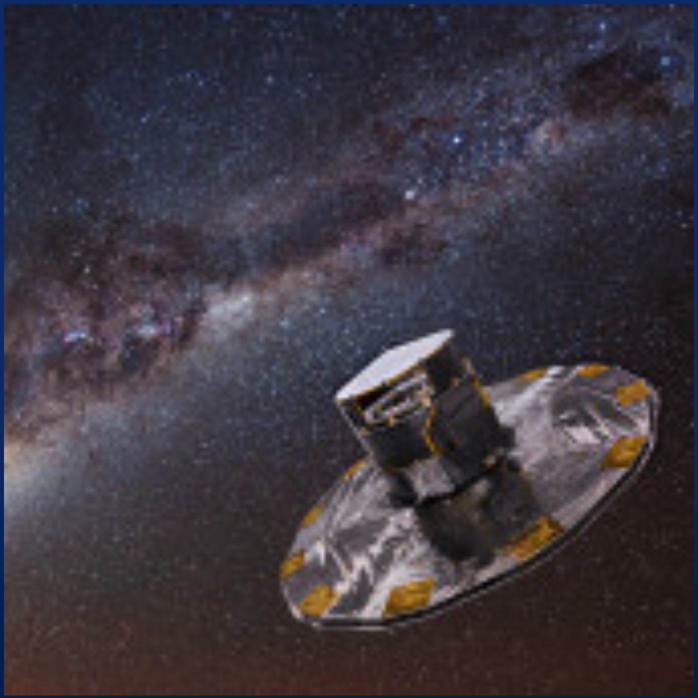
Parallax 0.314"

Manhattan taxi as viewed from Mexico City

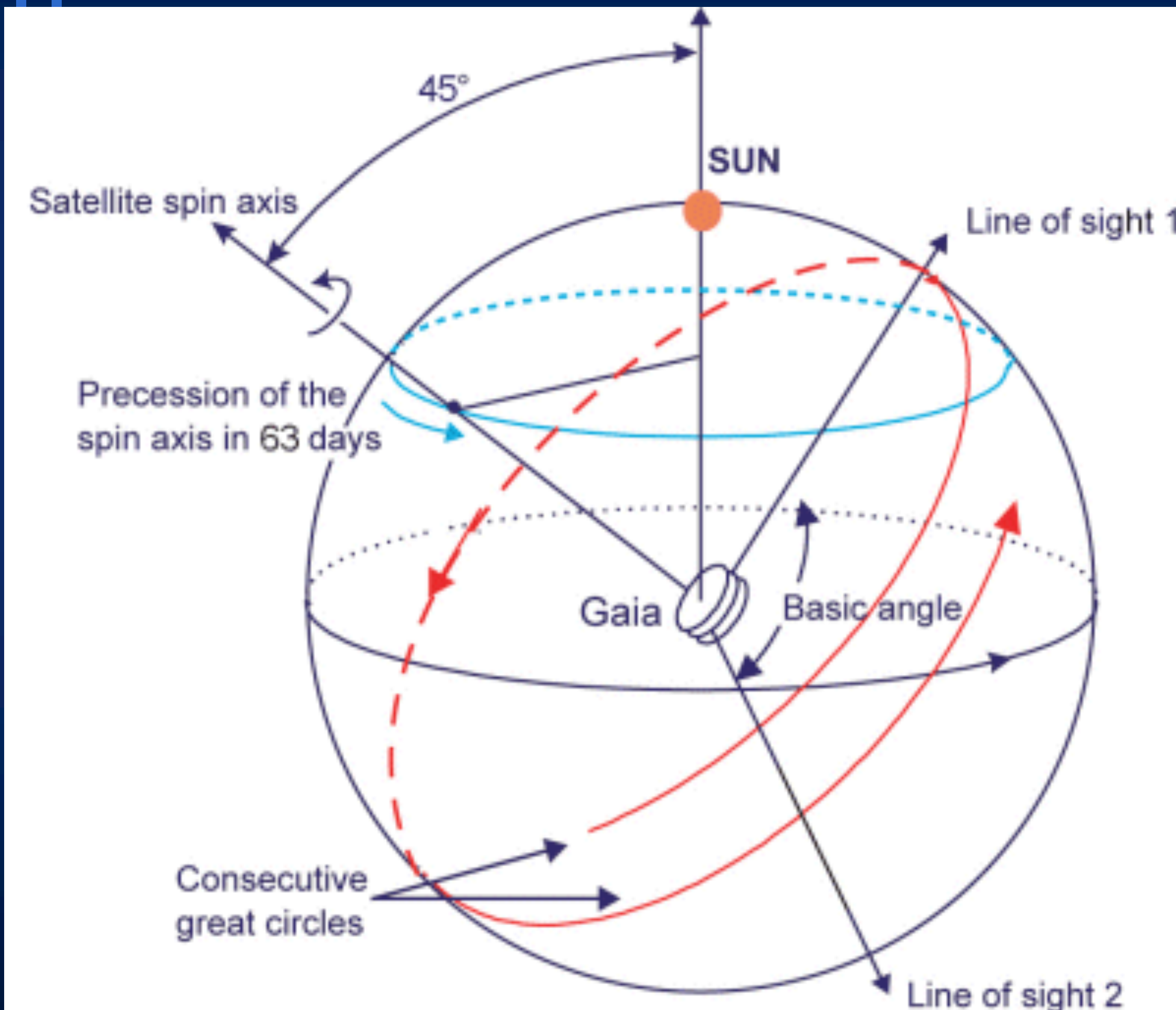


Friedrich Wilhelm Bessel.
Source: *Sternwarte, Universität Bonn.*

Gaia has measured parallax of 1.3 billion stars to 24 μarcsec



How Gaia Works

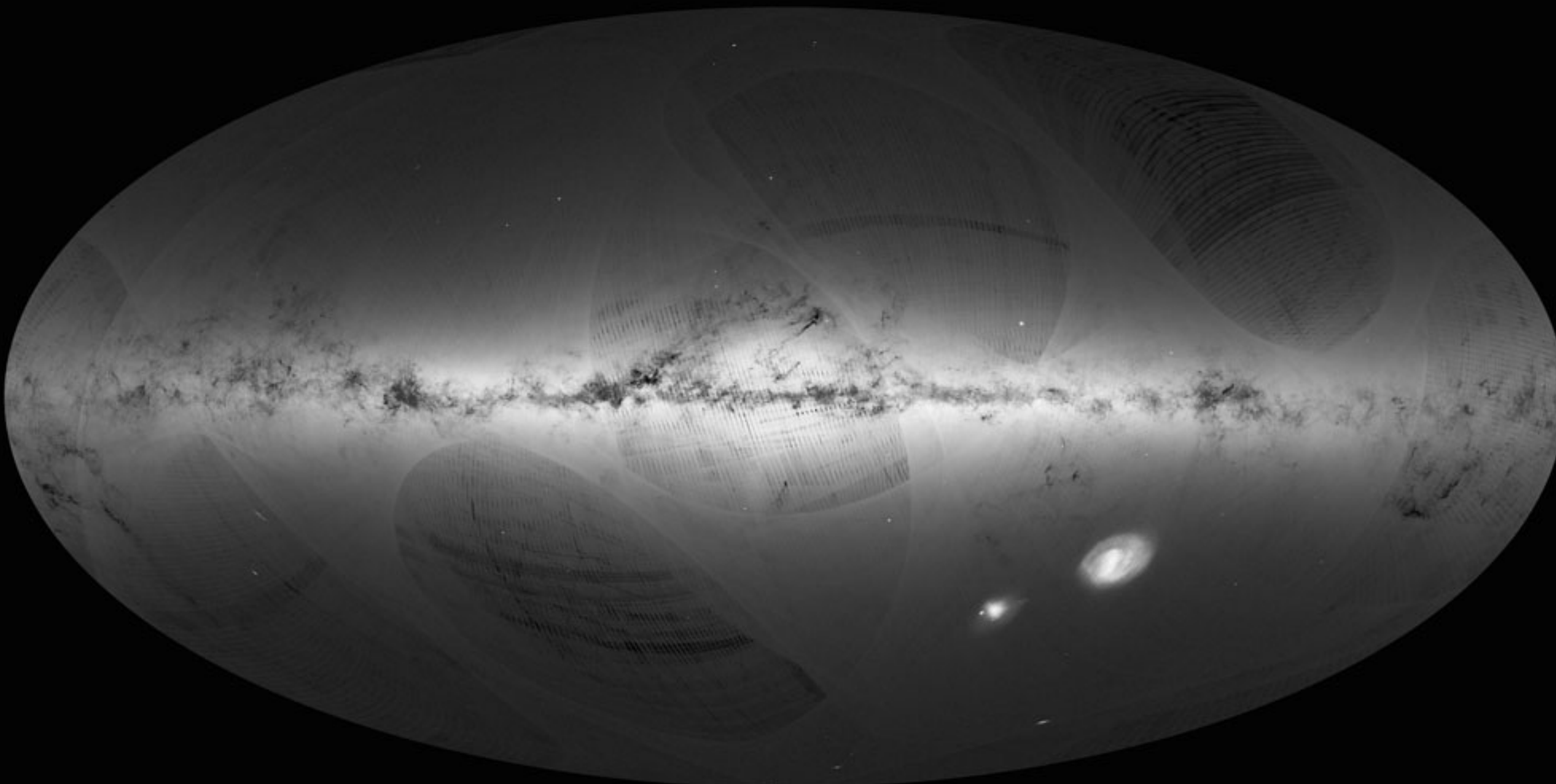


Gaia at L2

1) Spins around its axis every 6 hours
2) Axis precesses around Sun period 63 days
3) Each point in sky sampled ~70 times

ESA

Some Gaia Results



GAIA at a glance

Catalogue:
~1.3 billion stars to G = 20 mag

Sky density: mean density ~25 000 stars deg^{-2}

Accuracies: median parallax errors:
7 μas at G = 10 mag; 26 μas at G = 15 mag;
600 μas at G = 20 mag

Aside: Stellar Motions

- Before continuing with distances we must have a small diversion and discuss stellar motions.
- Beyond apparent motion due to parallax, many stars exhibit motion in a constant direction - proper motion.
- Velocity of a star can be divided into 2 components.

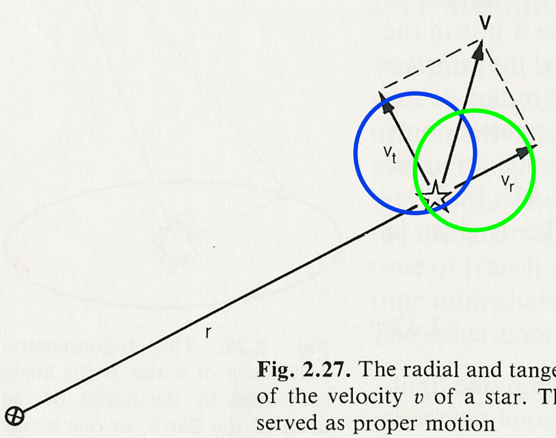
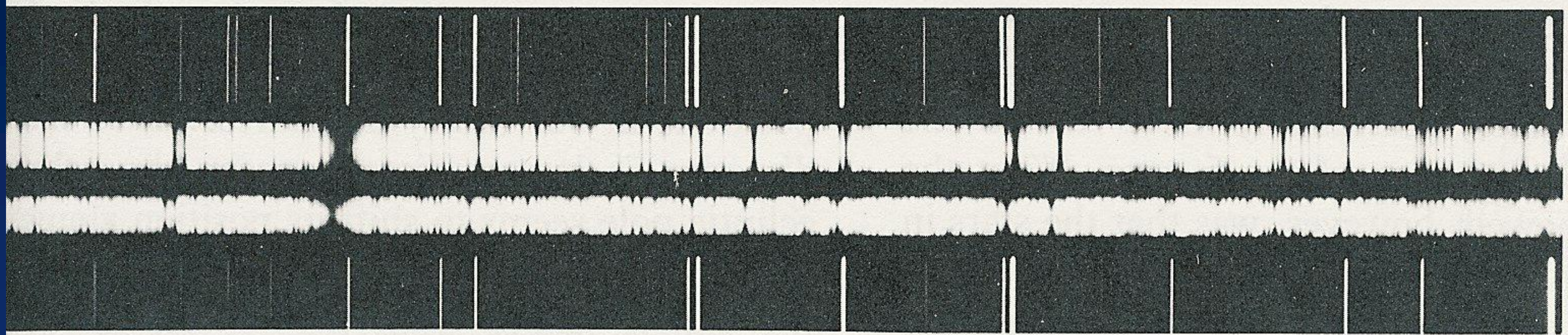


Fig. 2.27. The radial and tangen… of the velocity *v* of a star. The… served as proper motion

V_r is the radial velocity

V_t is tangential velocity

RADIAL VELOCITIES



e 22.4 Two spectrograms of Arcturus, taken six months apart. On July 1, 1939 the measured radial velocity was +18 km/s; on January 19, 1940, it was −32 km/s. ifference of 50 km/s is due to the orbital motion of the Earth. (Caltech/Palomar vatory)

Data obtained with spectrograph

$\Delta\lambda/\lambda_o = v/c$

Velocities of stars in our Galaxy range up to +/- 300 km/sec. A few up to 600 km/s (escape velocity from Galaxy). Typical for stars in disk is 30 km/sec.

PROPER MOTIONS p. 444 - 448

Measured over a period of years from direct images. Unit is "/year.

Largest measured Barnard's star 10.25"/year. Few 100 stars with PM > 1"/year. Note that PM will depend on distance.

Effect of proper motions

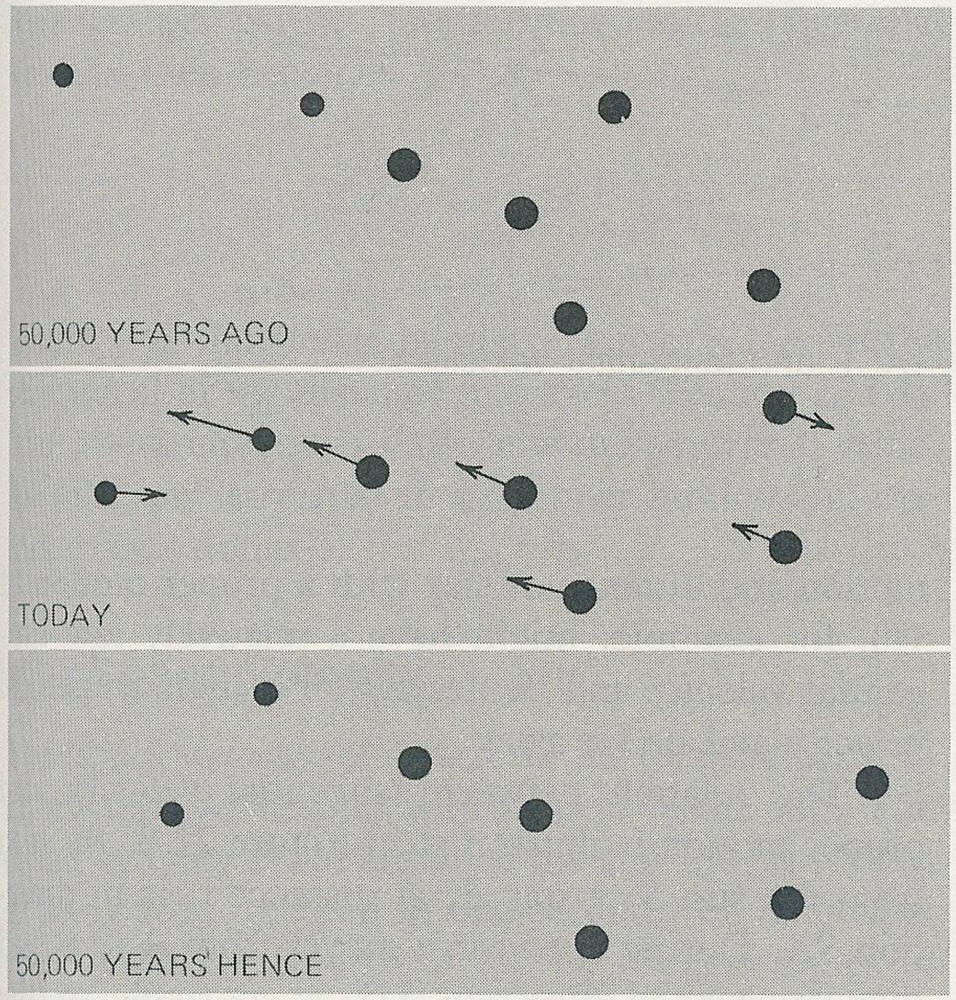
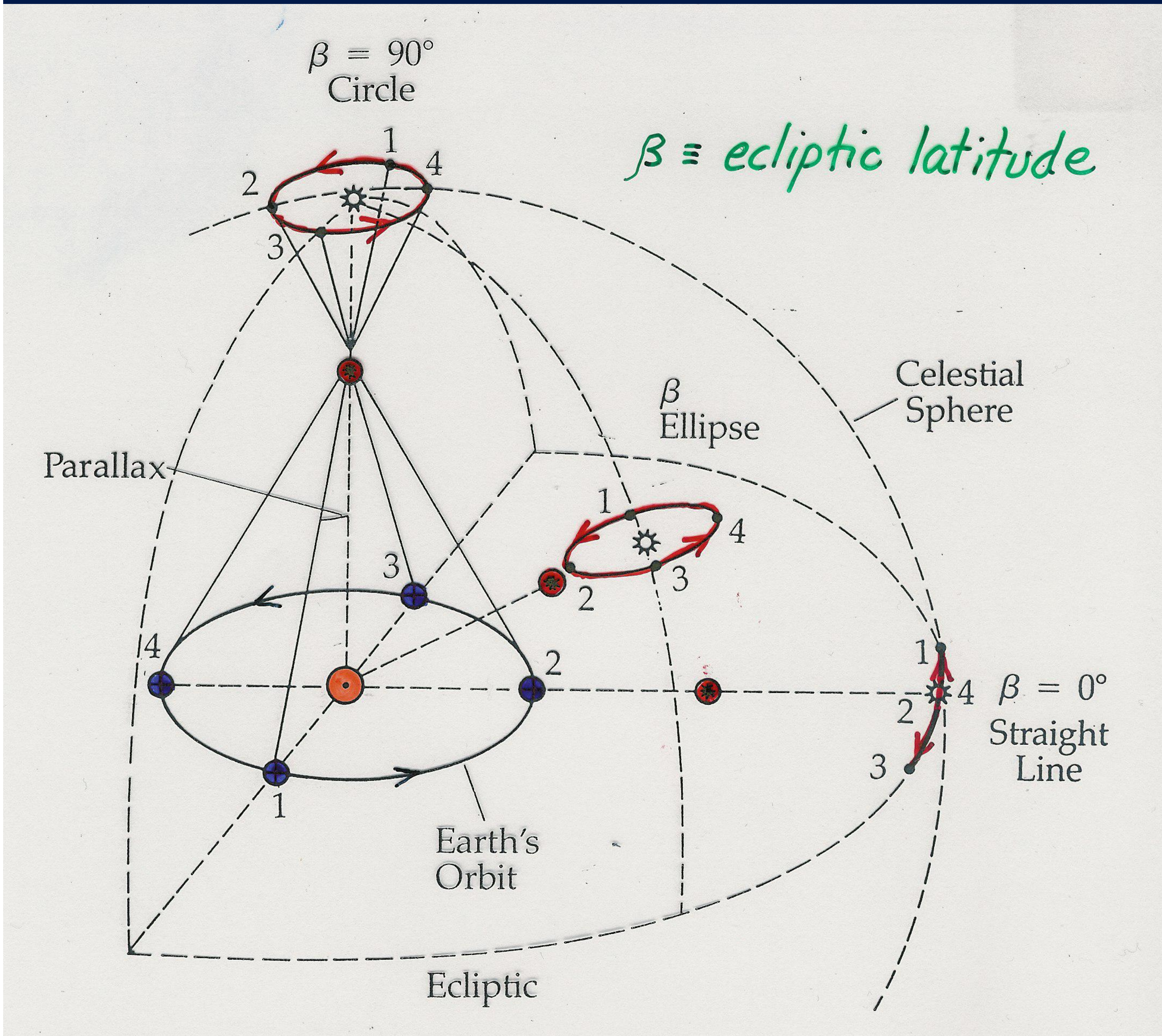


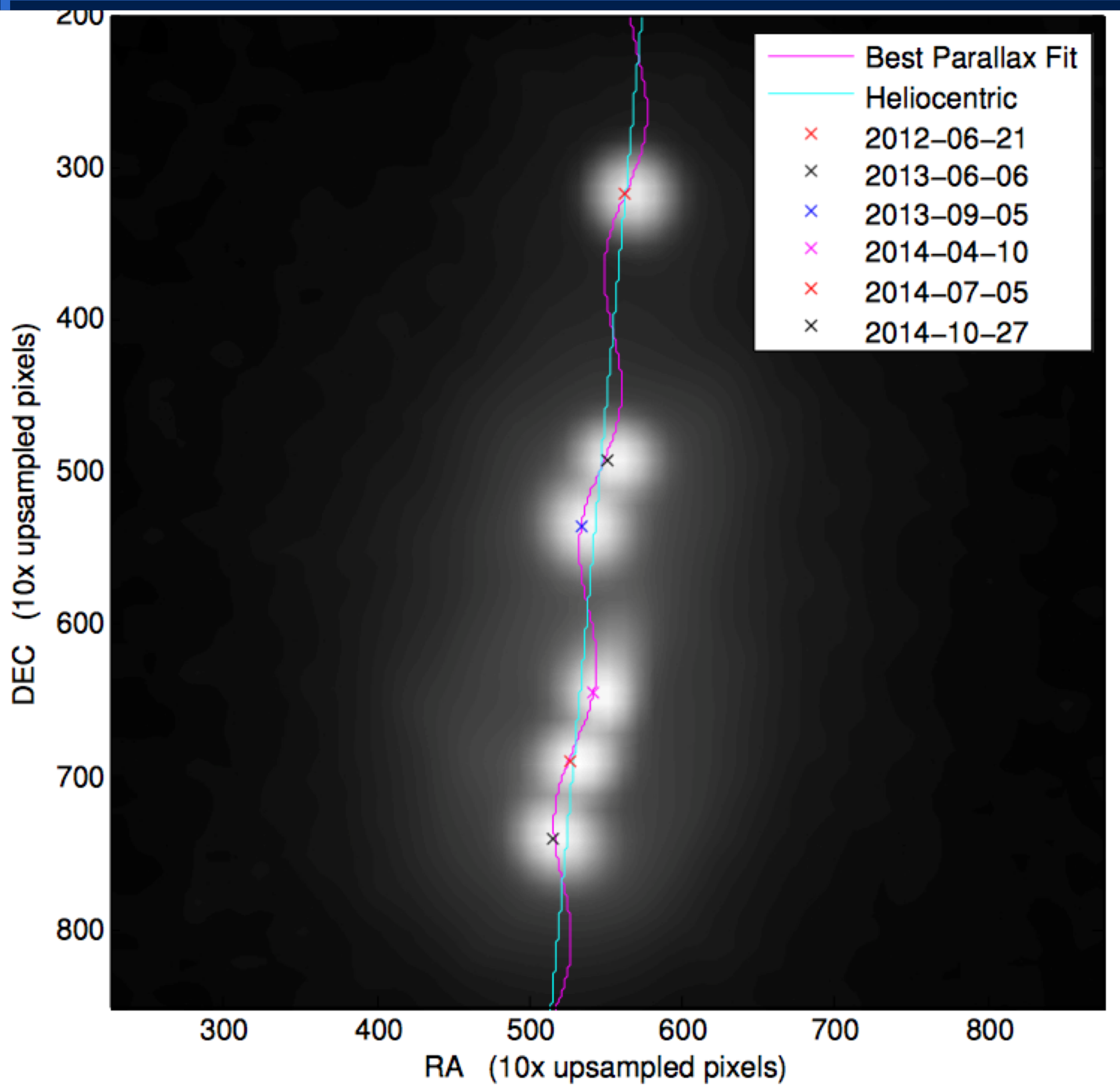
Figure 22.6 Appearance of the Big Dipper over 100,000 years.

Parallax and Position



This shows how parallax and proper motion are distingushed. Parallax repeats Itself yearly while proper motion does not. Solve for both simultaneously.

Parallax and Position



This shows how parallax and proper motion are distingushed. Parallax repeats Itself yearly while proper motion does not. Solve for both simultaneously.

Basic Properties of Stars p.309- 313

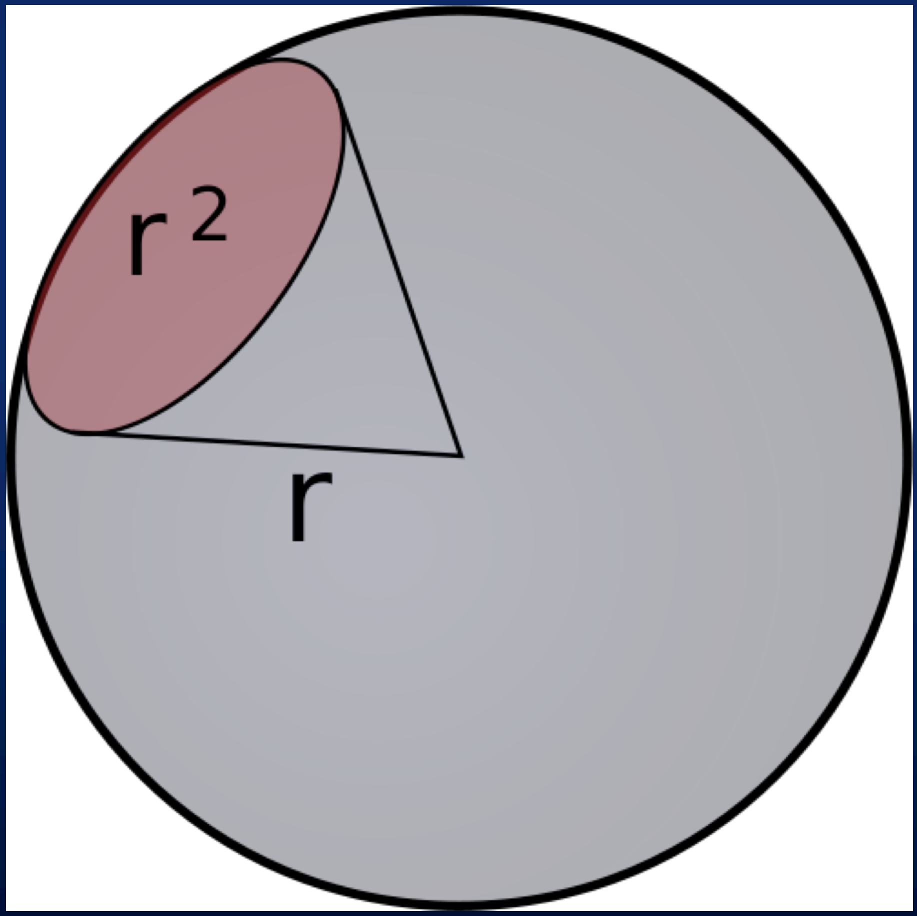
- Luminosities
- Fluxes
- Magnitudes
- Absolute magnitudes
- Distance Modulus

Solid Angle

- ***The solid angle**, Ω*, of an object is a measure of how big that object appears to an observer at that point. For instance, a small object nearby could subtend the same solid angle as a large object far away. The solid angle is proportional to the ***surface area***, *S*, of a projection of that object onto a ***sphere*** centered at that point, divided by the square of the sphere's radius, *R*. $\Omega = S/R^2$. The units of solid angle is ***steradian*** (abbreviated *sr*). Thus the solid angle of a sphere measured at its center is 4π sr ($4\pi r^2/r^2$).

Solid Angle

Also area on sphere which is equal in area to square of its radius subtends 1 steradian as seen from centre.



For Fun

1) What is the angular size of the Sun as seen from Earth (in arcsecs)?

Radius Sun = 7.0 x 10^5 km
Distance to Sun = 1.5 x 10^8 km

2) What is the solid angle of the Sun as seen from Earth?

3) What fraction of the sky does the disk of the Sun then cover?

Luminosities and magnitudes of stars § 13.2

- *Luminosity L is energy passing through closed surface encompassing the source (units-energy/time - eg watts)*

  If source (star) radiates isotropically, its radiation at distance r is evenly distributed on a spherical surface of area $4 \pi r^2$

- *Flux is then*

  $F = L / 4 \pi r^2$ *(w m*$^{-2}$*)*

- *F falls off as* $1 / r^2$
- *Inverse Square Law*
- *Solar constant is 1365 w m*$^{-2}$ *(experiment)*

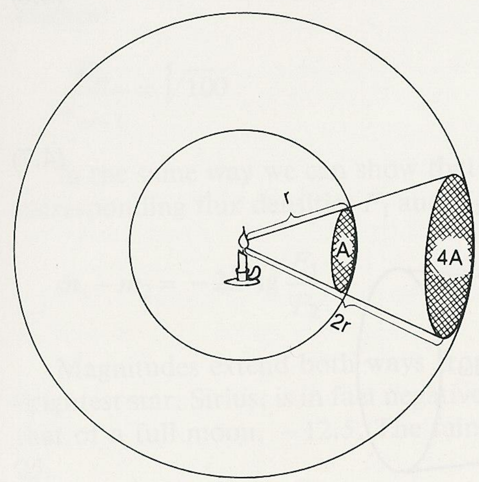
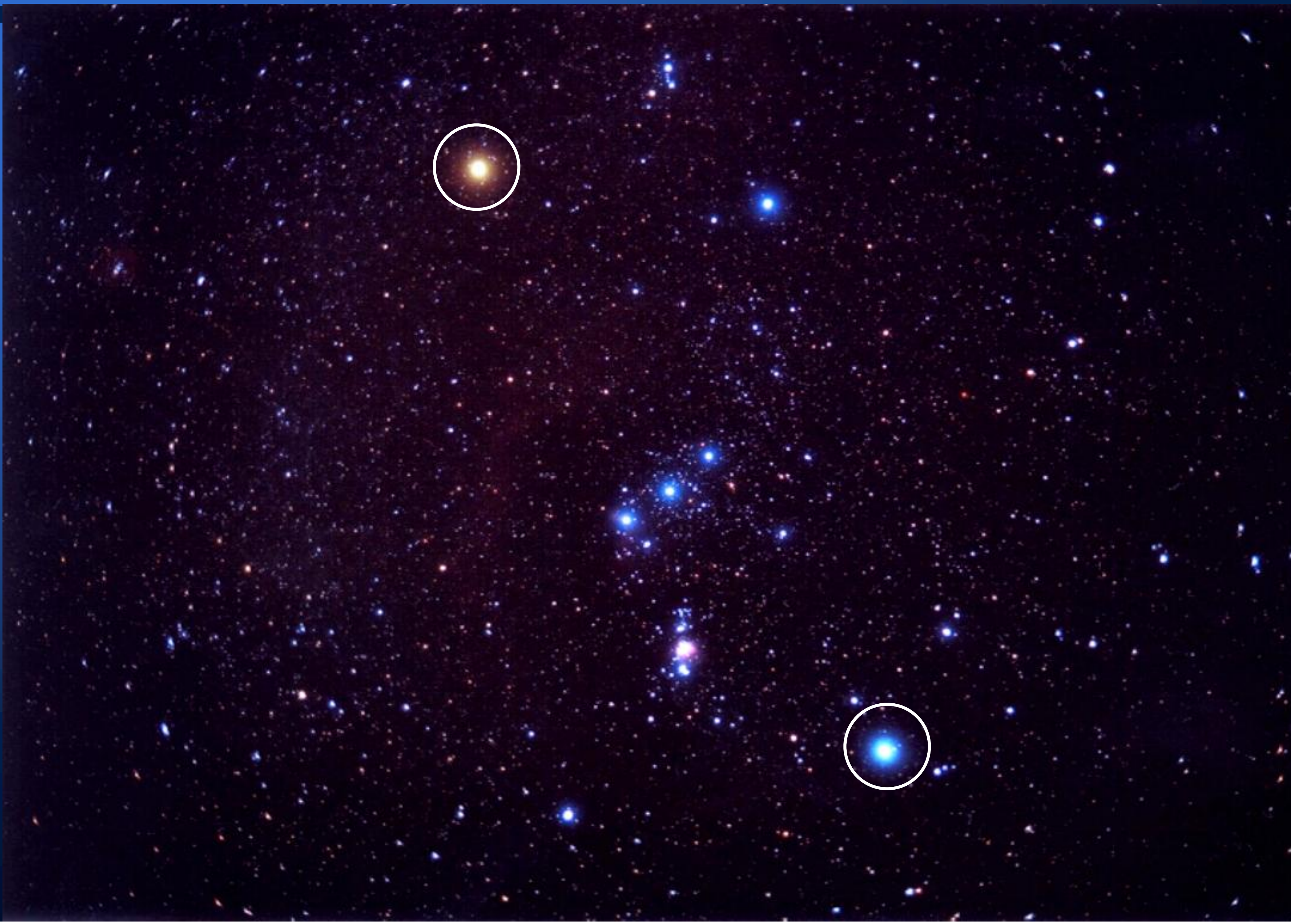


Fig. 4.3. An energy flux which at a distance r from a point source is distributed over an area A is spread over an area $4A$ at a distance $2r$. Thus the flux density decreases inversely proportional to the distance squared

Brightness, the magnitude scale
§ 13.2

- *In 120 BC, Greek astronomer, Hipparchus, ranked stars in terms of importance (ie. brightness) → "magnitude"*
- *1st magnitude were brightest → 6th magnitude faintest visible stars (later extended to 0 and -1)*
- *Without realizing it, Hipparchus based his scheme on the sensitivity of the human eye to flux - logarithmic scale, not a linear one.*
- *Perceived brightness ∝ log (actual flux)*

Rigel & Betelgeuse - 0^{th} Magnitude Stars



Brightness and the magnitude scale

Magnitude scale later standardized so that mag. = 1 is exactly 100 x brighter than mag. = 6

Difference of 5 mag = factor 100 in brightness

Difference of 1 mag = factor 2.512 in brightness i.e. $(2.512)^5 = 100$

Note: smaller mag is brighter star

We can quantify this definition of magnitude scale: Ratio of two brightness (flux) measurements is related to the corresponding magnitudes by $F_1/F_2 = 10^{0.4\,(m_2 - m_1)}$

F_1 and F_2 are fluxes and m_1 and m_2 are magnitudes

NB that it is F_1/F_2 and $m_2 - m_1$

Brightness and the magnitude scale

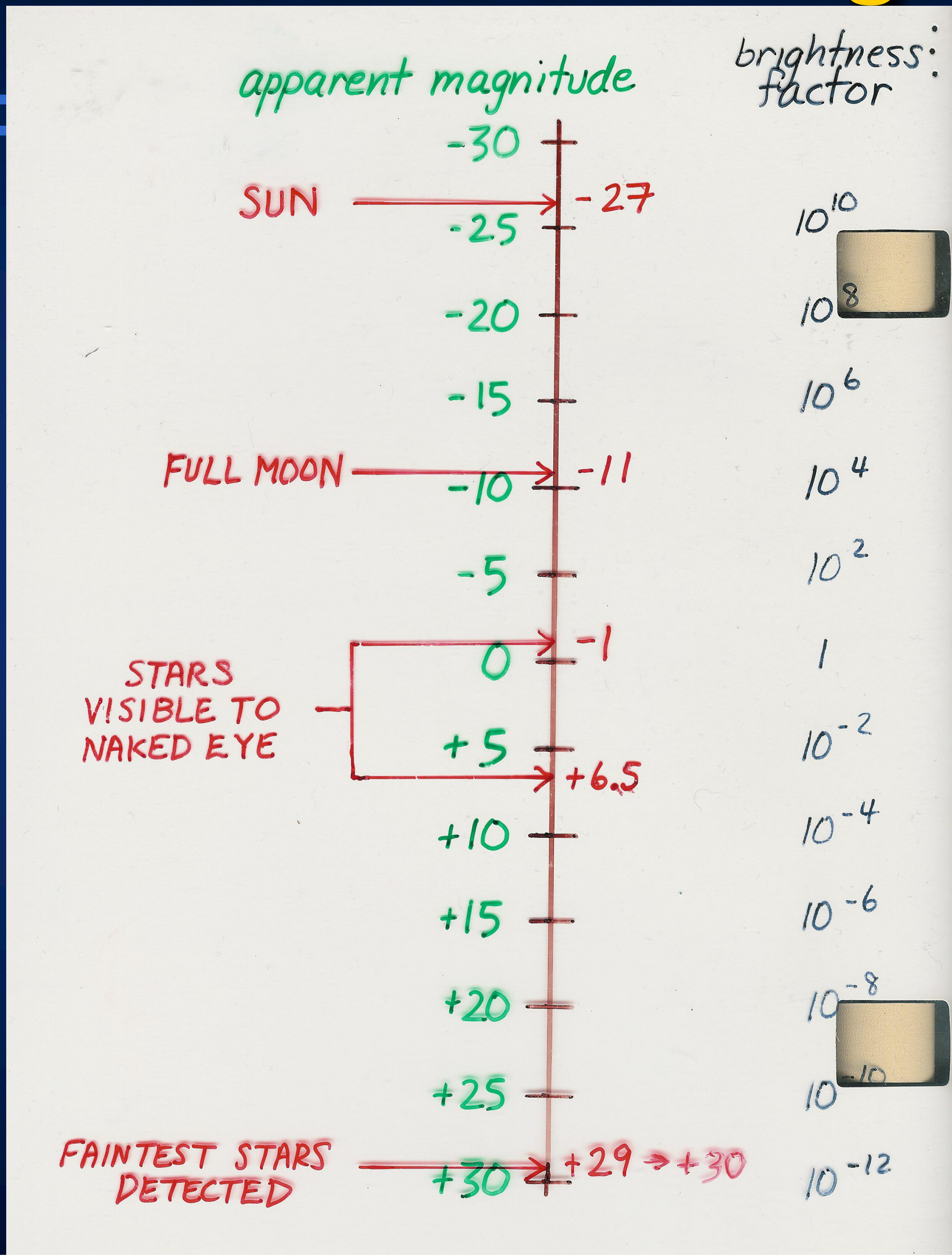
This is usually expressed in the form:

$$m_2 - m_1 = 2.5 \log_{10} (F_1/F_2)$$

Note that it is m_2 - m_1 on the left and F_1/F_2 on the right

ratio apparent brightness (F_1/F_2)	mag. difference $m_2 - m_1$
$1 = 10^0$	0
$10 = 10^1$	2.5
$100 = 10^2$	5.0
$1000 = 10^3$	7.5
$10{,}000 = 10^4$	10.0
10^8	20.0

Brightness and the magnitude scale



Brightness and the magnitude scale

- *Since brightness of a given star depends on its distance, we define:*
  - *<u>Apparent magnitude</u>, **m** (this represents flux) = magnitude measured from Earth*
  - *<u>Absolute magnitude</u>, **M** (this represents luminosity) = magnitude that would be measured from a standard distance of 10 parsecs (chosen arbitrarily)*
- $m - M = 2.5\log_{10}(F/f)$
- *Where F is the flux measured at 10 pc and f is flux measured at distance d to the star*

Brightness and the magnitude scale

Using inverse square law, $F/f = (L/4\pi 10^2) / (L/4\pi d^2)$ *L is energy output, we get*

$m - M = 2.5 \log_{10} (d/10)^2 = 5 \log_{10} (d/10) = 5 (\log_{10} d - \log_{10} 10)$

The last term is just = 1 so we have

$$m - M = 5 \log_{10} d - 5 \text{ or } m - M = 5 \log_{10} d/10$$

m - M is called the distance modulus and will appear often.

d is distance to the star in parsecs.