Astronomy, Astrophysics, and Cosmology

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Lesson I
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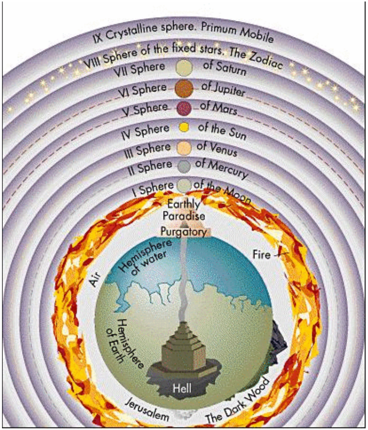
Night sky provides a strong impression of a changeless universe

- ✧ Clouds drift across the Moon ☞ on longer times Moon itself grows and shrinks
- ✧ Moon and planets move against the background of stars
- ✧ These are merely local phenomena caused by motions within our solar system
- ✧ Far beyond planets ☞ stars appear motionless

According to ancient cosmological belief ☞ stars
except for a few that appeared to move (the planets)
where fixed on sphere beyond last planet



The universe was self contained
and we (here on Earth) were at its center

Our view of universe dramatically changed after Galileo's telescopic observations:
we no longer place ourselves at the center and we view the universe as vastly larger

Is the Earth flat?

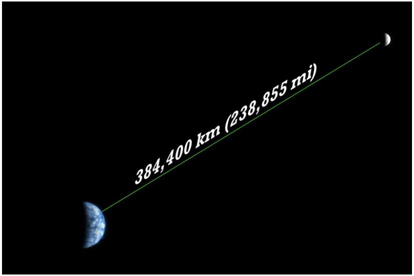
Distances involved are so large that we specify them in terms of the time it takes the light to travel a given distance

- light second ☞ $1 \text{ ls} = 1 \text{ s} \;\; 3 \times 10^8 \text{ m/s} = 3 \times 10^8 \text{m} = 300,000 \text{ km}$
- light minute ☞ $1 \text{ lm} = 18 \times 10^6 \text{ km}$
- light year ☞ $1 \text{ ly} = 2.998 \times 10^8 \text{ m/s} \cdot 3.156 \times 10^7 \text{ s/yr}$
  $= 9.46 \times 10^{15} \text{ m} \approx 10^{13} \text{ km}$

How long would it take the space shuttle to go 1 ly?

Shuttle orbits Earth @ 18,000 mph ☞ it would need $37,200$ yr

- For specifying distances to Sun and Moon we usually use km

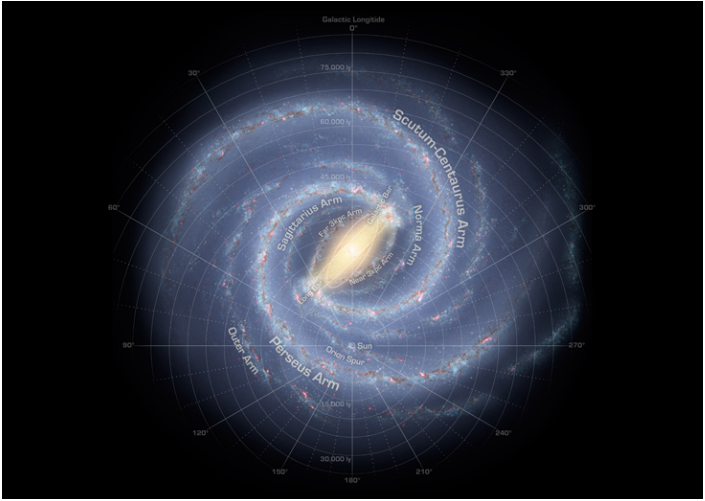


  but we could specify them in terms of light
- Earth-Moon distance is 384,000 km ☞ 1.28 ls.
- Earth-Sun distance is 150,000,000 km ☞ 8.3 lm
- Far out in the solar system
  Pluto is about 6×10^9 km from the Sun ☞ 6×10^{-4} ly
- Nearest star to us ☞ Proxima Centauri is about 4.3 ly away
- Nearest star is 10,000 times farther from us
  than outer reach of solar system

- On clear moonless nights thousands of stars with varying degrees of brightness can be seen ☞ as well as the long cloudy strip known as Milky Way
- Galileo first observed with his telescope that Milky Way is comprised of countless numbers of individual stars
- Half century later (about 1750) Thomas Wright suggested that Milky Way was a flat disc of stars extending to great distances in a plane which we call Galaxy (Greek for "milky way")

Milky Way over Quiver Tree Forest in southern Namibia

- Galaxy has diameter $\sim 100,000$ ly and thickness $\sim 2,000\ ly$
- It has a bulging central "nucleus" and spiral arms
- Our Sun is located half way from the Galactic center to the edge



some $26,000$ ly from the center

- ✧ Sun orbits Galactic center about once every 250 million years
- ✧ its speed is ➘

$$v = \frac{2\pi \quad 26,000 \times 10^{13}\ \mathrm{km}}{2.5 \times 10^{8}\ \mathrm{yr}\ 3.156 \times 10^{7}\ \mathrm{s/yr}} = 200\ \mathrm{km/s} \tag{1}$$

- ✧ Total mass of all stars can be estimated using orbital data of Sun
- ✧ Assume most of the mass is concentrated near center of Galaxy
- ✧ Sun and solar system (of total mass m)
  move in circular orbit around Galaxy center (of total mass M)
- ✧ Apply Newton's laws

$$\frac{GMm}{r^2} = m\frac{v^2}{r} \tag{2}$$

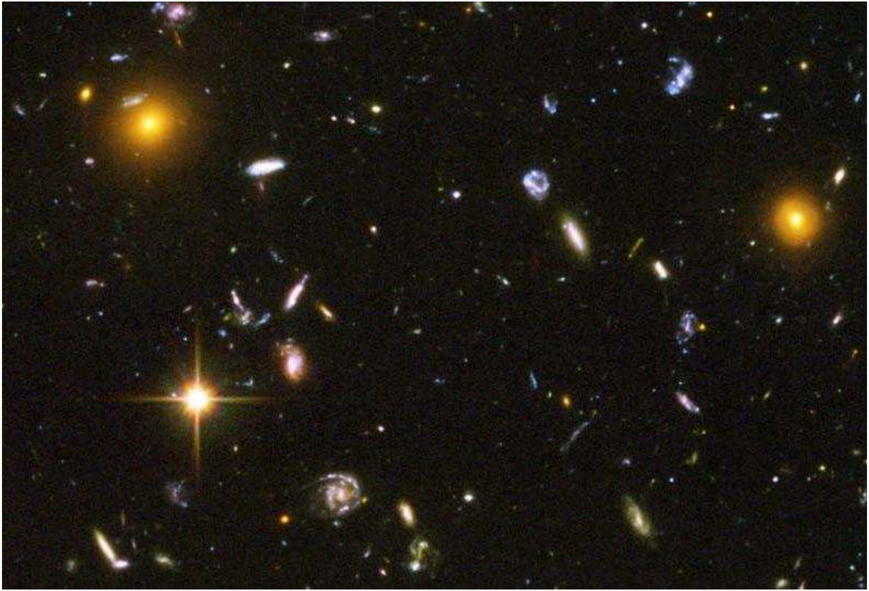
$G = 6.674 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$

$$M = \frac{r\,v^2}{G} \approx 2 \times 10^{41}\ \mathrm{kg} \tag{3}$$

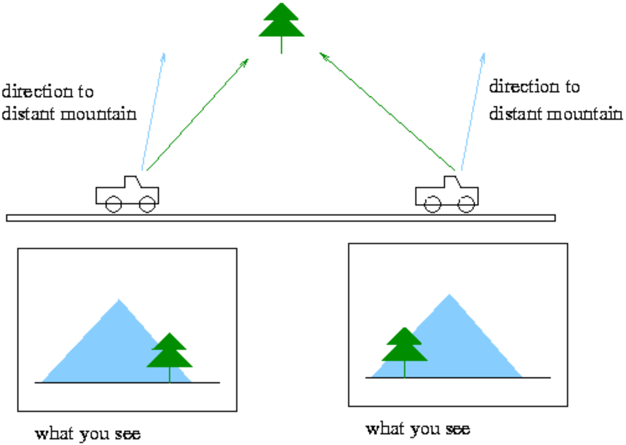
- ✧ Assuming all stars in Galaxy are similar to Sun ($M_\odot \approx 2 \times 10^{30}$ kg) we conclude that there are roughly 10^{11} stars in the Galaxy

- In addition to stars we can see with telescope
  many faint cloudy patches that were once called “nebulae”
- Those in the constellations of Andromeda and Orion
  can actually be discerned with naked eye on clear night
- At first it was not universally accepted
  that these objects were extragalactic
- Very large telescopes constructed in XX century
  resolved individual stars within these extragalactic objects
  that also contain spiral arms
- It became logical that nebulae must be galaxies similar to ours
- Distance to nearest spiral galaxy ☞ Andromeda over 2 million ly
  a distance 20 times greater than the diameter of our Galaxy
- Today it is thought there are $\sim 4 \times 10^{10}$ galaxies
  that is as many galaxies as there are stars in the Galaxy

Deep field of view as seen by Hubble Space Telescope

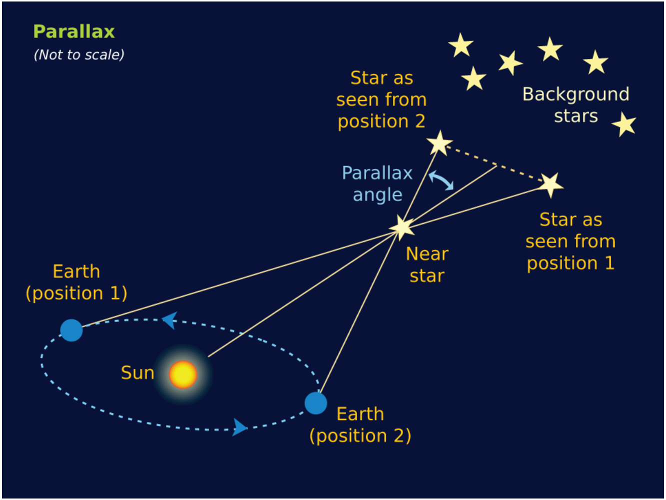


- Parallax ☞ apparent displacement of an object because of a change in observer's point of view
- To see how this effect works ☞ hold your hand out in front of you and look at it with your left eye closed, then your right eye closed
- Your hand will appear to move against the background

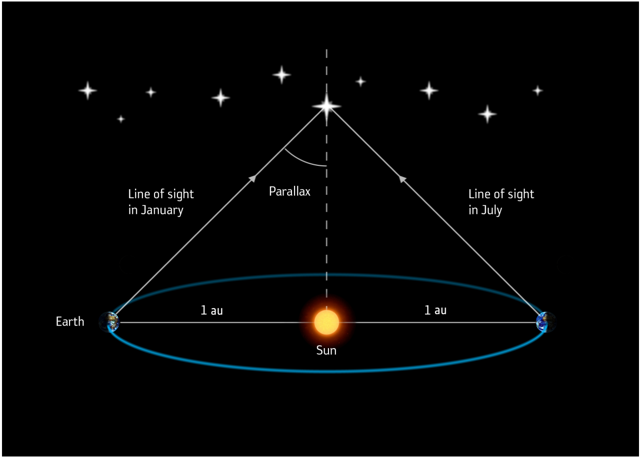


Stellar parallax

Apparent motion of a star against background of more distant stars due to Earth's motion around Sun



- Sighting angle of star relative to plane of Earth's orbit (usually indicated by θ) can be determined at 2 different times separated by six months
- Since we know distance d from Earth to Sun we can determine distance D to star



E.g. ☞ if parallax angle is $p \equiv \phi = 0.00006^\circ$
From trigonometry ☞ $\tan \phi = d/D$
and since distance to Sun is $d = 1.5 \times 10^8$ km
distance to star is

$$D = \frac{d}{\tan \phi} \approx \frac{d}{\phi} = \frac{1.5 \times 10^8 \text{ km}}{1 \times 10^{-6}} = 1.5 \times 10^{14} \text{ km} \sim 15 \text{ ly} \tag{4}$$

- Star distances ☞ often specified in terms of parallax angles given in seconds of arc ☞ $1'' = 1/3600^\circ$
- Star distances ☞ often specified in parsecs (meaning *par*allax angle in *sec*onds of arc)
- 1 parsec is defined as $1/\phi$ with ϕ in seconds
- E.g. ☞ if $\phi = 6 \times 10^{-5\,\circ}$ ➠ star is @ $D = 4.5$ pc

- Useful parameter for star or galaxy is its luminosity
- Total luminosity of a star is given by
  product of its surface area and radiation emitted per area

$$L = 4\pi R^2 \sigma T^4 \tag{5}$$

- Total power leaving $1\ \mathrm{m}^2$ of star surface ☞ radiant flux
  is surface brightness integrated over all frequencies
  and relevant solid angle

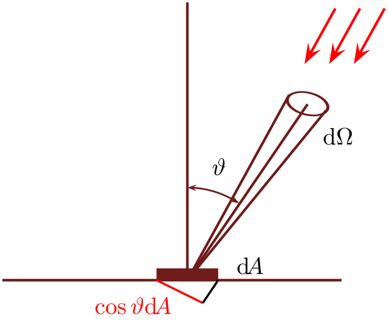
$$F(T) = \pi \int_0^\infty B_\nu d\nu = \frac{2\pi}{c^2 h^3} (kT)^4 \int_0^\infty \frac{x^3\, dx}{e^x - 1} = \sigma T^4 \tag{6}$$

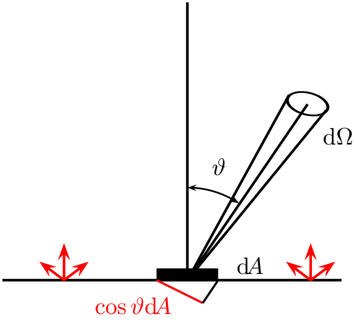
- Validity of inverse-square law $F \propto 1/r^2$ @ $r > R$ outside star
  relies on the assumptions that no radiation is absorbed
  and that relativistic effects can be neglected
- 2nd condition is satisfied if relative velocity of observer and source
  are small compared to speed of light

If D is distance from star to Earth

$$D = \sqrt{\frac{L}{4\pi b}} \tag{7}$$

b ☞ radiant flux at surface of Earth or surface brightness



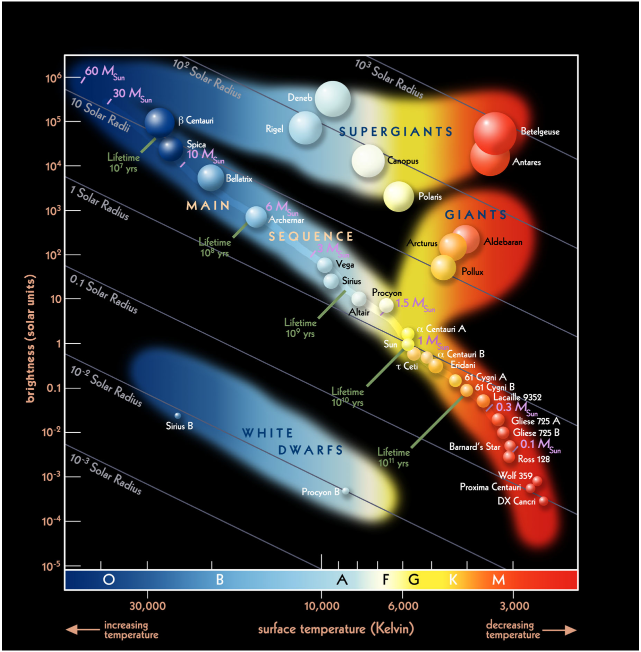


- Another important parameter of a star is its surface temperature T
- T is determined from spectrum of electromagnetic frequencies
- Stars are fairly good approximations of blackbodies
- Wavelength at the peak of the spectrum
  is related to Kelvin temperature by Wien's law

$$\lambda_{\max} T = 2.9 \times 10^{-3}\ \mathrm{m\,K} \tag{8}$$

Hertzsprung-Russell diagram

- For most stars ☞ color is related to absolute luminosity and therefore to mass
- HR diagram ☞ useful way to present this relationship
- Horizontal axis shows T and vertical axis L
- Most stars fall along diagonal band termed ☞ main sequence
- Starting at lowest right we find coolest stars redish in color they are least luminous and therefore low in mass
- Further up towards left we find hotter and more luminous stars that are whitish like our Sun
- Still farther up more massive and more luminousbluish stars
- There are also stars that fall outside main sequence
- Above and to the right we find extremely large stars with high luminosity but with low (redish) color temperature
- At lower left there are stars of low luminosity but with high T


60 M_{Sun}
30 M_{Sun}
10^2 Solar Radius
10^3 Solar Radius
10 Solar Radii
β Centauri
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Antares
Spica
10 M_{Sun}
Lifetime 10^7 yrs
Bellatrix
Canopus
Polaris
1 Solar Radius
MAIN
6 M_{Sun}
Achernar
GIANTS
SEQUENCE
Arcturus
Aldebaran
Lifetime 10^8 yrs
3 M_{Sun}
Vega
Pollux
Sirius
Procyon
0.1 Solar Radius
Altair
1.5 M_{Sun}
Lifetime 10^9 yrs
α Centauri A
Sun
1 M_{Sun}
α Centauri B
ε Eridani
τ Ceti
10^{-2} Solar Radius
Lifetime 10^{10} yrs
61 Cygni A
61 Cygni B
Lacaille 9352
0.3 M_{Sun}
Sirius B
Gliese 725 A
Gliese 725 B
WHITE
DWARFS
Barnard's Star
0.1 M_{Sun}
Lifetime 10^{11} yrs
Ross 128
10^{-3} Solar Radius
Wolf 359
Proxima Centauri
Procyon B
DX Cancri
brightness (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature