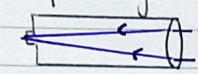
Astrophysics

Lecture 1

Astrophysics is the oldest science - in Religion, mythology, astrology, and then science.

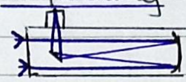
Telescopes.

Refracting



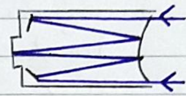
expensive
colour issues

Reflecting



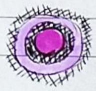
cheaper
blurring

Catadioptric



Best
expensive

Aperture has diameter D, and when you look at stars they have rings around them from diffraction



Diffraction limit - minimal angle separation of 2 stars so they can be distinguished by telescope

looks like  in a scope.

sep^

$$\Delta\theta = \frac{1.22\lambda}{D}$$

Seeing.

Starlight through the layered atmosphere makes it look different, and placed differently aka Twinkling.
degrades diffraction limits from 0.5 to 2 arcseconds.

How do we beat it?

Adaptive optics - computer calculating how crap weather is and changes scope optics to beat it.

Lasers - see how the laser light changes and deforms

Just go into Space!

Lecture 2

Blackbody Radiation

Emits all EM Radiation absorbed, and absorbs all radiation incident.

$L = A\sigma T^4$ $\quad W = \lambda T$ $\quad$ from Alevel $\quad F = \frac{L}{A}$ or $\frac{L}{4\pi d^2}$

from Cosmology ×

Planck Radiation formulae:

Energy per unit volume per unit:

frequency or wavelength

$$S_\nu = \frac{8\pi h}{c^3} \frac{\nu^3}{e^{h\nu/kT} - 1} \qquad S_\lambda = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Magnitudes

Made by Hipparchus - 1 is brightest to 6 dimmest
Galileo saw fainter than 6 ⇐ telescope invention.

Magnitude is logarithmic

A change in 5 magnitudes = 100x brightness change
∴ 1 mag change is $100^{1/5}$ change = 2.512

For 2 stars w/ magnitudes m_1 & m_2

Brightness ratio: $100^{(m_1 - m_2)/5}$

Flux equation: $\frac{F_2}{F_1} = 100^{(m_1 - m_2)/5}$

> Magnitudes are all ratios so we use (α Lyra) Vega as a basic standard with ~~mag~~ mag 0

Hence: $-2.5\log_{10}\left(\frac{F_2}{F_1}\right)$ ~~$2.512\log_{10}$~~ $= m_1 - m_2$

and

$$m_1 - m_2 = 5\log_{10}\frac{d_1}{d_2}$$

Apparent magnitude - brightness from Earth (m)
Absolute magnitude - brightness from 10pc (M)

$$m - M = (5\log_{10}(d) - 5)$$

Filters

limits wavelengths observed to make better observations
Bandpass ($\Delta\lambda$) = bandwidth and has central wavelength λ_0.

Photometry is the practice of measuring a star's brightness/flux. Nowadays, it is common to use CCD cameras to measure the ~~#~~ γ from a star. Adding pixel values and subtracting background radiation gives us the intensity. This needs multiple steps + comparisons + pre-calibration

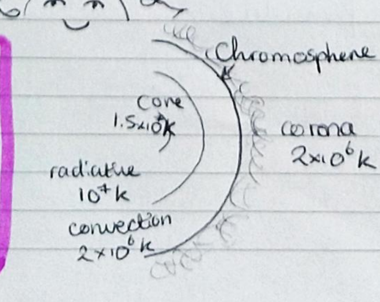
> 1 angstrom = 10^{-10} m

Spectroscopy is splitting the star's light into a continuum. It shows lines, which shows: Elemental/molecular composition, temperature & pressure, rotation, magnetic field strength, velocity, mass loss, etc...

> Resolution $R = \frac{\lambda}{\Delta\lambda}$

Lecture 3

The Sun



Stats

1.5×10^{6} km away
$\theta = \frac{1}{2}°$
2×10^{30} kg $= M_\odot$
$T_{eff} = 5770$K
74% H, 24% He, 2%

The Core

- Thermonuclear reactions $\approx 0.25 R_\odot$
- $T \approx 1.5 \times 10^7 k$ $\rho \approx 150'000 \ kgm^{-3}$
- Nuclear burning just about completely stops after 0.25R.

Radiative Zone

- $0.25 - 0.7 R_\odot$ ($0.7 R_\odot$ = Interface layer or Tachocline)
- Energy radiates outward - photon scattering - very slow (10^5 yrs)
- ρ is from 20'000 (centremost) to 200 kgm^{-3}.
- T falls from 7×10^6 to 2×10^6

Tachocline - between Radiative & convective.

- Magnetic field may be generated here by shearing (changes in fluid velocity)

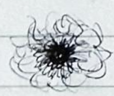
Convective Zone

- $0.7 R_\odot - 1 R_\odot$
- $T = 2 \times 10^6 k$ (cold enough for "metals" to have their electrons) photons from Radiative zone can't get past, traps heat [called opacity]
- Photons make fluid unstable and boils ⟹ convection current.
- Surface $T \approx 5770 k$ $\rho \approx 0.0002 \ kgm^{-3}$

The Photosphere

- Visible Surface, 100km thick, non uniform intensity.

Sunspots



in pairs
Strong magnetic fields

granules
convection cells ± 5mins only
≈1000km

Faculae

light areas of concentrated magnetic field.

Chromosphere

T ≈ 20'000K - gas strongly in Hα line (6563 Angstrom)

- In Hα can see chromospheric network, plages, filaments, prominences, spicules.

Transition Region

- Rapid temp change, hydrogen completely ionised. emission mostly of C IV, O IV, Si IV (UV mostly)

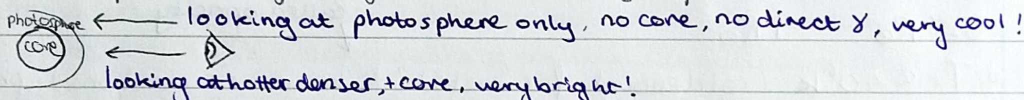
Corona

- $T \sim 10^6$ K, see it w eclipses!
- Emission mostly of Ca, Fe. H, He, N, C, O completely ionised & stripped.
- Can see loops, plumes, streamers, holes! Use X-ray!

Solar Phenomenae

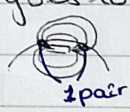
Limb Darkening

Centre of sun is brighter / yellower than edges of sun (also redder).



Sunspots

- cools down to ≈ 3'800 k. Intense B-field that interferes / halts
- convection in that area (hence it cools) goes to 0.1 T.
- usually has a group of sunspots in an active region.



Prominences or filaments

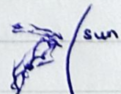
- Streams of chromospheric gas. Couple types:

Quiescent - long lived (weeks) curtains slowly falling from corona → Chromosphere

Active - few hours & very loopy and can become solar flare.

Flares

- small ones happen a few times an hour or every few hours one large one.
- 10k-300k km 5 mins to rise 20 + mins to fall. $\approx 10^6$ K. Energies up to 10^{30} J
- They eject energy + cosmic rays.



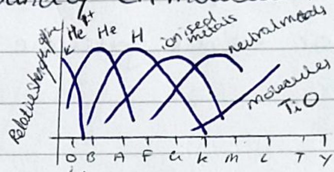
Solar Wind.

Solar gravity isn't enough to hold high energy particles. Flows off into space through coronal holes or solar flares. Sun loses $\approx 10^{-13}$ M☉/yr. $V_0 = 300\,kms^{-1}$ $V_{at Earth} = 400\,kms^{-1}$

Lecture 4

Stellar Classification

Harvard System OBAFGKMLTY - mostly based on hydrogen spectral lines. Most important ones are Balmer series. They also used ionised He, Fe, Ca, H & K, G band of CH molecule, and others.



Strongest lines (almost accurate/to scale)

also has 9-1 class system between.

It is a temperature classification system.

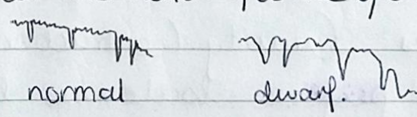
Spectral differences primarily reflect differences in surface temperature.

O - 50'000K av no Hydrogen lines. Strong He^+
B - 20'000K av weak hydrogen. Strong neutral He
A - 10'000K Strong H, weak Ca^+
F - 7'500K Strong Ca^+, weak H,
G - 6'000K Strong metals . .

Yerkes (MKK) system. estimate surface gravity $g = \frac{GM}{R^2}$ to define Giants Dwarves.

Ia luminous supergiant
Ib less luminous ↑
II luminous giants
III Giants
IV Sub giants
V MS dwarf
VI Sub dwarf.

dwarves have small R so g is higher.
dwarfs have higher pressure + surface density.
under high pressure atoms collide more frequently,
collisions shorten lifetime of excited state ∴ lines broaden



Special Mentions

WR Wolf-Rayet, He mostly, fast dying w/ large solar wind.
C Carbon, Red (Super)giants near death w/ excess carbon
D white dwarf (subclasses ABOQZCX)
LTY Brown dwarf, failures!

Populations

Population 1 stars, young stars in spiral arms (like sun), in open clusters, ~2% metals. The Pleiades is an example.

Population 2 stars, old stars, first stars with only ~0.01% metals. Centre of galaxy or elliptic galaxies, globular clusters.

Colour

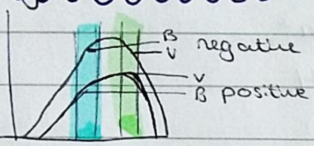
Difference between the brightness of stars in 2 filters. Filters U, B, V, R, I

for example B-V colour = mag from B - mag from V ← colour index

$$CI = m_{\lambda_1} - m_{\lambda_2}$$

You can use U-B, B-V, B-R, V-R, R-I, it all works!

Why is it important?



Hotter stars have more negative CIs.

You can replace Temp with CI in a HR diagram!

better for observational astronomer → $x = CI$ like B-V & $y = |mag|$ gives a colour-magnitude diagram.

If you can observe the CI,(m) you can find M using a HR diagram and calculate distance with $m - M = 5\log d - 5$. This method is spectroscopic parallax.

Lecture 5

Stellar Structure

Hydrostatic Equilibrium.

2 main forces: Gravity (contraction) & Pressure (expansion) when there's perfect balance between the 2, we have hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho(r)\left(\frac{GM}{R^2}\right) = -g\,\rho(r)$$

change of pressure with radius.

Surface gravity (when distance $r = R$)

don't actually multiply r!

The Sun's central pressure

$$\rho_{average} = \frac{M_\odot}{4/3 \pi R_\odot^3} \approx 1410 \ kgm^{-3}$$

← approximate, ρ does change with r.

$$\frac{dP}{dr} = -\rho(r) \left/ \frac{GM}{R^2} \right/$$ assume $\frac{dP}{dr} \approx \frac{P_{surface} - P_{centre}}{R}$ and $P_{surface} = 0$

so $\frac{dP}{dr} \approx -P_{centre}/R$

Hence

$$P_{centre} \approx \frac{GM \rho_{average}}{R} \approx 2.7 \times 10^{14} \ N/m^2$$ A lot!

Adding in Ideal Gas Laws (Marcus)

$$P = nkT$$

n: No Particles, k: Boltzmann's constant

μ = average mass of particles

$$\frac{1}{\mu} = \frac{m_H n}{\rho}$$ for stars:

m_H = Proton mass

$$\frac{1}{\mu} = 2X + \frac{3}{4}Y + \frac{1}{2}Z \approx \boxed{1.6}$$

X mass fraction of H
Y is for Helium
Z is metals.

The Sun's Central Temperature

rearrange the 2nd equation:

$$n = \frac{\rho}{\mu m_H}$$ add in $P = nkT$

$$T = \frac{P \mu m_H}{\rho k}$$ all with respect to r

using results before gives us $T_c \approx 1.2 \times 10^7$ K.
The gas in the centre is ionised but neutral... it's plasma!

Cores have high enough temperatures to fuse light elements together. In each P-P chain reaction:
Energy released = $(4 \, {}^1_1H - {}^4_2He)c^2 = (6.7 \times 10^{-27} - 6.6 \times 10^{-27})c^2$
$= 4.3 \times 10^{-12}$ J small but mighty!

So How Long Will The Sun Live (as type V)

≈10% of sun's volume has fusion conditions.

$$\text{Total Energy available} = \text{Energy per reaction} \times \frac{\text{total mass for fusion}}{\text{mass in each reaction}}$$

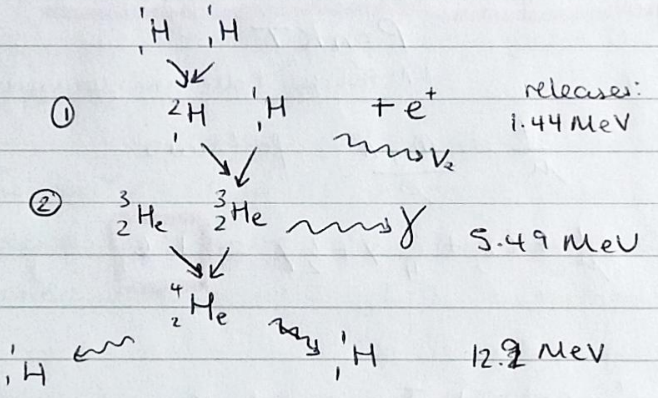
$$= 4.3\times10^{-12} \times \frac{0.1\,M_\odot}{4\ {}^1_1H \text{ atom mass}} = 1.27\times10^{44}\,J$$

↑ mighty

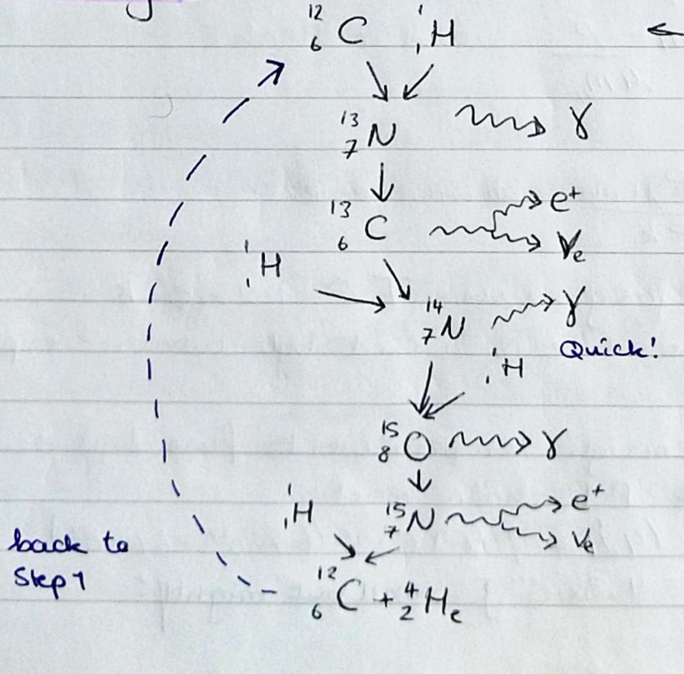
$$\text{lifetime} = \frac{\text{Total Energy}}{\text{Power output}\,(L_\odot)} = 3.3\times10^{17}\,s \text{ or } 10^{10} \text{ years!}$$

Fusion

PP1 chain



CNO cycle



← Carbon isn't used because it's a catalyst.

$T > 1.6\times10^7\,K$

It's for bigger stars ($>1.1\,M_\odot$), which have Carbon (population 1 stars).

Triple α Big hot stars only! No babies

^4_2He + ^4_2He → ^8_4Be ⇝ γ (← Quick)

^8_4Be + ^4_2He → $^{12}_6C$ ⇝ γ

triple α is also similar for Ne, O, Mg .... Fe.

lectweb

Life of Stars

Nebula → protostar → smol → Red Giant → Planetary Nebula → White Dwarf   <8 M☉

Nebula → protostar → big → Red Supergiant → Supernova → Neutron star   >8 M☉

Supernova → Collapsar   unsure

Birth

Stars are born in molecular clouds, like stellar nurseries.

Jeans-Mass (mass for a cloud to collapse into a star)

for a cloud with mass M, radius R, No particles N each with mass m and overall temperature T:

Potential Energy $U \approx -\text{constant}\ \frac{GM(Nm)}{R}$

Kinetic Energy $K \approx \frac{3}{2}NkT$

For collapse: $|U| > K$ so $\frac{GMNm}{R} > NkT$

Jeans Mass → $M_J > \left(\frac{kT}{Gm}\right)R$

Molecular Cloud (H_2 Region) collapses, either from fluctuations or external agitation (shockwaves)

As it collapses, PE gets converted to KE + radiation, KE is dissipated and radiation escapes, low temp & pressure, its a protostar.

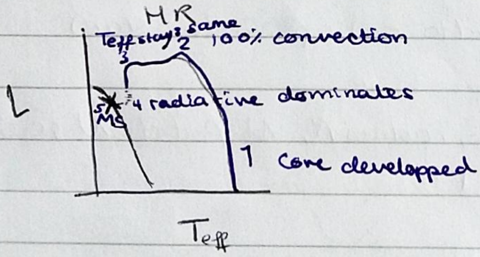
Collapse continues until the core is dense and optically thick ($\tau \geq 1$)
Now radiation gets trapped $\Rightarrow$ core heats up, collapse halts, and eventually hydrostatic equilibrium is established.

Now we have a Pre Main Sequence Star.

Temperature is low, and the star is basically 100% convective zone. The star contracts slowly, so the core heats up. The temperature at the surface doesn't change, so the luminosity drops and we start to see limb darkening (opacity ⇓) The core initiates radiative transport, so we start to get the 3 layers.

Radiation dominates convection, but with enough collapse the Temp is high enough for fusion. Fusion becomes the main releaser of energy. Goodbye contraction, hello equilibrium!

The star is now a Zero Age MS star (ZAMS). This takes ≈ 20 million years.



Some stars have Protoplanetary Disks, which are cold gas & dust. Planets sweep out lanes in the disks

Mass - luminosity Relation

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^\alpha$$

$\alpha = 2.3$ for dimmed stars below $0.43 M_\odot$ & $\alpha = 4$ more luminous stars at man $0.43 M_\odot$

Overall $\alpha \approx 3.3$ for everything else.

$$\left(\frac{t}{t_\odot}\right) = \left(\frac{M}{M_\odot}\right)^{-2.3}$$

(t = time)

So we can get an estimate for lifetime of a star during MS phase

In the Sun's evolution:

After 10 billion years, most of H is used up. T_{core} increases for He fusion and so the star brightens & expands.

But before that!...

Hydrogen is used up, core halts. Pressure drops and contractions start. The non-core H is pulled in and raised in temperature. He fusion starts, but with a H shell around He core. ρ increases as H → He and adds to the core.

Next...

Too much He gets added, the core contracts. Energy generation goes turbo and the outer layers (envelope that stores energy) expand.

The radius increases, but T_{eff} decreases, the Sun moves ⇒ on HR.

The opacity has increased, energy carried by convection dominates, the radius keeps increasing and T_{eff} keeps decreasing. But because convection is so efficient, luminosity increases.

The star is moving to RG Branch. Contraction keeps occuring until T_{core} = 100 million K. Triple α starts. He fusion begins!

He

Triple α heats core quickly, because it increases temp, energy, and that speeds up rate of reaction. This thermal runway is called Helium Flash, only a few minutes but uses 60-80% of Helium.

Core pressure increases, so it expands and cools, stopping He burning temporarily.

Outer layer & core contract again until T is enough for fusion again. He burnt in core, H burnt in shell. Now a subgiant

When core is Carbon, core contracts to burn outer He, expands again. This makes the star unstable & pulse, but it's now a giant on Asymptotic Giant Branch.

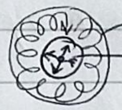
Thermal Pulses are cyclic. core stops fusion, contracts, heats up enough, fusion again. expands.
Energy gets rapidly transported to the surface via convection, Sometimes so rapidly that it makes a superwind and removes all the outer layers... Planetary Nebula

lecture 7

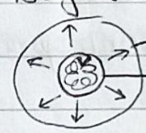
For Bigger Stars.

For very big stars, the main fusion is CNO ($T_{core} > 10$ million K) where 4H → He for only about 1 million years (O Type specifically)

Sunlike stars



Big stars



When H is gone, core contracts and H burns in a shell around He core. He core gets denser, contracts & heats up, H shell fuses quicker and outer layer expands T_{eff} cools.

Opacity increases, convection increases transport of energy to the surface. luminosity increases and moves to Red Giant Branch.

Core contracts until He fuses w/ triple α. NO Helium flash

He fusion

Core expands, luminosity drops. Slowly, T_{eff} rises from He fusion
He in core is gone, Carbon C core contracts and heats up. The now H and He shell fuses faster and outer layer expands. AGBranch

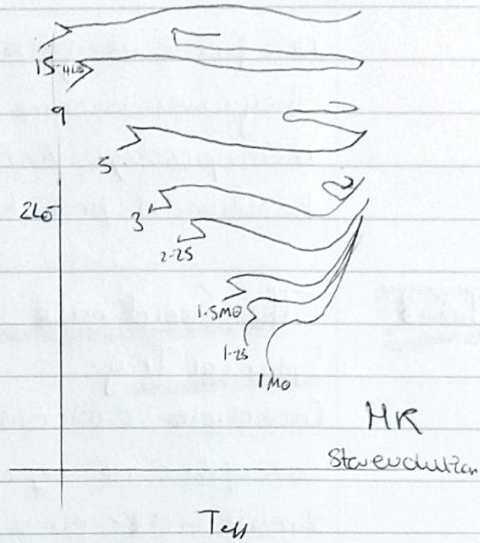
C fusion

Small big stars:
uncertain - heating & Cooling pulses stars (Thermal pulses) will drive a strong wind - strip material - Planetary nebula. If bigger: Supernova.

Bigger stars 5-8 $M_\odot$
Carbon core ignites $^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$
then oxygen maybe... Supernova

And Even BIGGER stars $> 8 M_\odot$...

Big big stars $> 8 M_\odot$



Large mass loss, Luminosity mostly constant

mass loss ∝ (10^{-6} to 10^{-7} $M_\odot$/yr)

Burns H, He, C but also:

$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$ at 10^{8} K

$^{12}C + {}^{12}C \rightarrow {}^{23}Na + {}^{1}H$
$\rightarrow {}^{23}Mg + n$ (← isotope)
$\rightarrow {}^{24}Mg + \gamma$
} at 6×10^{8} K

$^{16}O + {}^{16}O \rightarrow {}^{24}Mg + 2\,{}^{4}He$
$\rightarrow {}^{28}Si + 4\,{}^{4}He$
$\rightarrow {}^{31}P + {}^{1}H$
$\rightarrow {}^{31}S + n$ (← isotope)
$\rightarrow {}^{32}S + \gamma$
} at 6×10^{8} K

and other triple α

$^{28}Si + {}^{4}He \rightarrow {}^{32}S$

$^{32}S + {}^{4}He \rightarrow {}^{36}Ar$ and in the biggest stars ^{56}Fe

It can't go past ^{56}Fe because it is the biggest binding energy, anything bigger will need more energy to fuse, a waste of time

If the $> 8 M_\odot$ star's core mass is bigger than Chandrasekhar limit ($1.4 M_\odot$) then electron degeneracy won't support the core. No white dwarf, too fat to wave! neutron degeneracy occurs if $T > 6\times10^{9}$ by photodisintegration of ^{56}Fe and ^{4}He. It creates neutrons!

$^{56}Fe \rightarrow 13\,{}^{4}He + 4n$
$^{4}He \rightarrow 2p + 2n$
$p + e^{-} \rightarrow n + \bar{\nu}$.
} requires 100 MeV. core energy used quickly.

Neutron degeneracy - neutrons create pressure because it's so dense. The core can't collapse anymore and creates shockwave. It rips apart like mad! Type II Supernova w/ neutron star

CHONKY STARS $> 25 M_\odot$

Neutron degeneracy can't help this big boy... black hole

Now for the very small Stars $<0.08 M_\odot$

They never become MS stars. Gravitational collapse doesn't heat them up enough for PP1. if they're $>14 M_{jup}$ or $>14 M_{21}$ can fuse Deuterium ^2H for short time. These stars cool off and are Brown Dwarves.

Lecture 8

The Coordinate System.

Spherical Trig

Great circle - circle on the sphere (circumference) where the centre is the centre of the circle eg equator and not any other latitude line! ← Shortest distance between 2 points

Small circle - circle on sphere not including centre eg lat line.

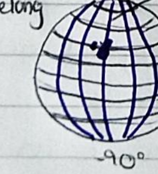
Spherical angle - angle between 2 Great circles eg 2 meridians.

Spherical Triangle - triangle bound by 3 great circles.

1 nautical mile = 1 arc minute $1/60°$ along a great circle

eg 0°N to 90°N North → Equator 90° = 5'400' = 5'400 Nautical miles. 1 Nm = 1.852 km so from 0°N to 90°N = 10'000.8 km

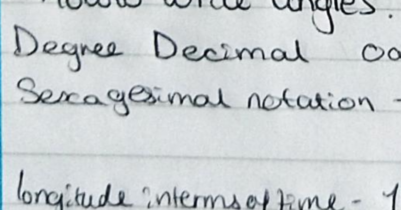
Spherical Law of Cosines:



$\cos a = \cos b \cos c + \sin b \sin c \cos A$

Similar to cosine rule $a^2 = b^2 + c^2 - 2bc\cos A$

Coordinate system 1: latitude & longitude



There is also a paris meridian, 'cause they were mad over Bonaparte's exile.

How to write angles.

Degree Decimal Oadby Scopes 52.623° N

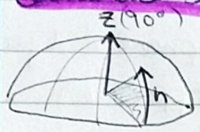
Sexagesimal notation - integer degree, arcminutes, arcseconds

eg oadby = 01°07'25.6" W, 52°37'22.4" N

longitude in terms of time - 1 hour = 15° so 1 degree = 4 minutes

- Oadby scope y is -0h4m29.7s. take decimal, ÷15, then convert back to sexagesimal.

Coordinate system 2: Altazimuth



altitude h = angular distance of object above horizon.

Zenith distance = 90 - h

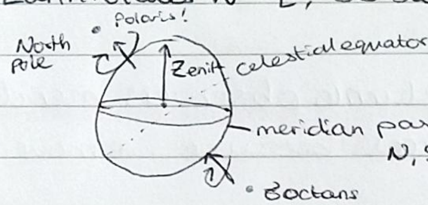
Azimuth A · angular bearing of object East

Altazimuth always changes with Earth's rotation!

The celestial Sphere

Imaginary infinite sphere w/ you at centre

Earth rotates W → E, so stars sun etc move E → W.



North pole is at angle ∅ = Latitude

Circumpolar stars - never set (within ∅ at latitude ∅)

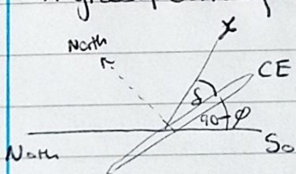
when a star crosses the meridian, it transits it and reaches maximum altitude.

Stars within - ∅ (for North observer) will never be seen above horizon.

Coordinate System 3: Declination (latitude)

DEC δ 0° equator, -90° N/S pole. measured from equator.

highest point of star is 90° - ∅. Declination = (90° - ∅) + δ



so angle of star is (90 - ∅) + δ. due south

If the star is due North

we use 180 - ((90 - ∅) + δ) due North.

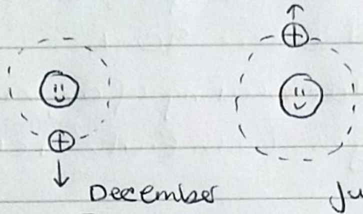
Right Ascension (longitude)

time. 0h 0m 0.00s = First Point of Aries (♈) occurs at vernal (spring) Equinox when Sun's position moves from South hemi to North.

Lecture 9

Motion of The Sun

Apparent position of the Sun moves around the sphere in 1 year.
Best stars to look at $\alpha = \alpha_{sun} + 12hr$ (directly opposite)



The Zodiac are the constellations where the Sun passes through.

Sidereal Day

Time taken for stars to return to exact place in sky (360°)
23h 56m 4.09s

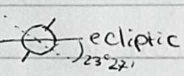
Solar Day

Synodic day - time for Sun to return to observer's meridian.
24hrs. (a bit more than Sidereal because we move in an orbit)

The Ecliptic

The path the Sun and most planets (they formed from the same disk!) follows (plane of Earth's orbit) Earth's spin axis = 23° 27' called the obliquity.
The ecliptic is at 0 Dec (equator) when:
- Vernal Equinox 21 or 22 March (First point of Aries)
- Autumnal Equinox 21 or 22 September in Libra.

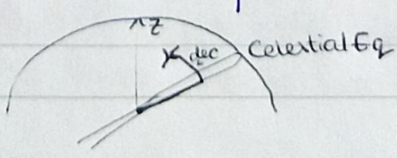
The ecliptic is max at:
June 21/22 or Dec 21/22 Solstice at +23° 27' and -23° 27'



Lecture 10

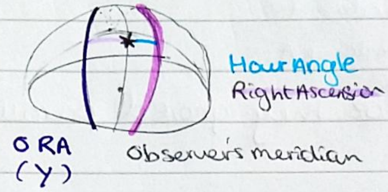
Hour Angle HA

Good to know which stars should be good to observe
Star's position relative to observer's meridian. it increases Westwards so with time. -12h to +12h. Stars with -ve HA are yet to rise.
= RA of star - Observer's Meridian in hours
Tip Good stars are within 3hrs of meridian



Sidereal Time

HA from ORA (γ) as a measure of Sidereal Time. The hour angle from γ is Local Sidereal Time LST.



LST = HA + RA

when 0 = HA then RA = LST when it is highest in sky. Stars w/ this are best to see.

Leicester LST = 03h22m tonight (13/11) midnight.
Lat = 52° 38' N
Long = 1° 8' W

Universal Time

UT - Greenwich Mean Time a 0° Longitude.

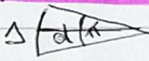
Lecture 11

Geometric Parallax

angular displacement relative to background object

π_g used. $d = \frac{\Delta}{\pi_g}$ — displacement

distance, parallax



$\frac{\Delta}{2} = d \tan \frac{\pi_g}{2}$

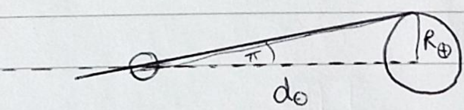
$d = \frac{\Delta}{2 \tan \frac{\pi_g}{2}}$

approx $\tan \frac{\pi_g}{2} \approx \frac{\pi_g}{2}$

$d = \frac{\Delta}{\pi_g}$

Solar Parallax

Angle subtended at Earth's radius at the distance of the Sun:

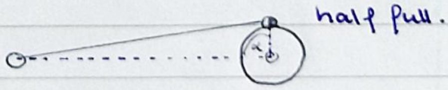


$\frac{R_\oplus}{d_\odot} = \pi_s$ ← so small

This can't be done, because π_s is so small and there are no background stars during the day

To find $d_\odot$, Aristarchus measured:

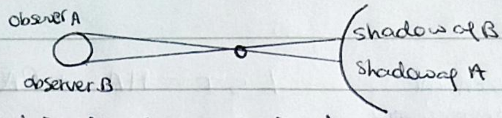
$\frac{d_{E to moon}}{d_{E to sun}} = \cos \alpha$



Moon's terminator - sharp half line between light & dark side when half full. He got it very wrong!

Another Method : Venus' Transit

As Venus transits it produces a shadow. 2 far away observers will see the shadow displaced due to parallax



3 scientists tried, but failed coz they ignored parallax

Trigonometric Parallax

parallax = ½ anglur change at a distance of 1 parsec.

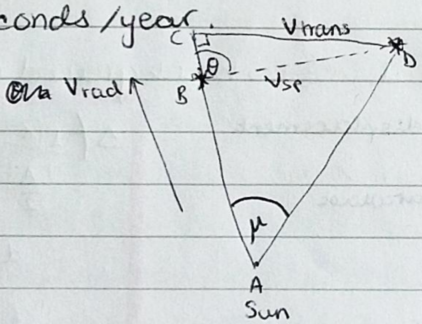
1 AU ⇒ 1 arcsecond

$$d = \frac{1}{\pi''}$$

d ← parsec; π″ ← arcseconds.

Propermotion

Stars drift in position across sky propermotion μ is measured in arcSeconds / year.



Star moves from B → D in 1 year.

$$\sin\mu = \frac{V_{trans}}{d}$$

if μ is small $\mu = \frac{V_{trans}}{d}$ ← AU per year.

if $\pi = \frac{1}{d}$ then $V_{trans} = 4.74 \frac{\mu''}{\pi''}$