ASTRO PHYSYCS

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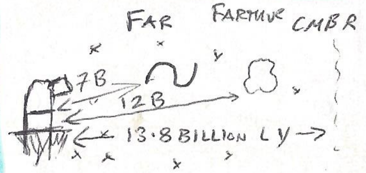
INTRODUCTION TO GRAVITATION & ASTROPHYSICS

FAR Away means BACK IN TIME, as it takes light time to travel the distance

$$1 \text{ light-year} = (\text{speed of light}) \times (1 \text{ year}) \approx 9.46 \times 10^{12} \text{ km}$$

unit of distance

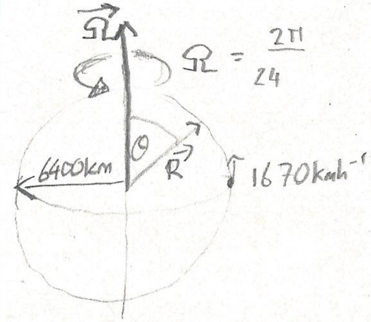


OUR movement through space:

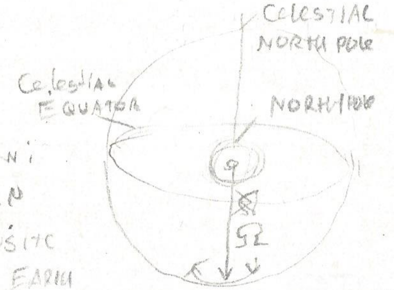
GIVEN BY $\vec{v} = \vec{\Omega} \times \vec{r}$

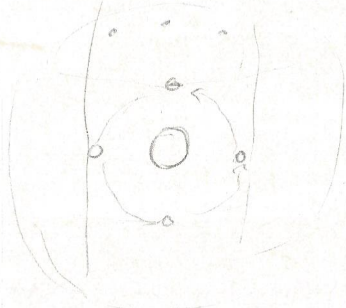
$$|V_{TANGENTIAL}| = \Omega r \sin\theta$$

- earth moves through solarsystem
- sun moves around galaxy



CELESTIAL SPHERE





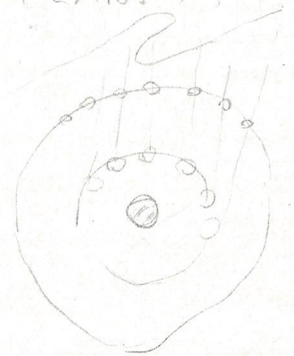
DURINAL MOTION: APPARENT MOTION OF STARS OPPOSITE TO MOTION OF EARTH

- DIFFERENT VISIBILITY OF STARS THROUGH YEAR

PARALLAX

PLANETS

PLANETS



STARS

- small
- use to measure distance to them

Newtons Law of Universal Gravitation: $\vec{F}_{12} = -G\frac{M_1M_2}{r^2}\hat{r}$

⊙ Sun Symbol ⊕ Earth Symbol

Acceleration due to gravity: $\boxed{g = -\frac{GM}{r^2}\hat{r}}$

Gravitational Potential Energy

$$\Delta U = -W = -\int_{r_1}^{r_2}\vec{F}\cdot dr = -Gm_1m_2\int_{r_1}^{r_2}\frac{1}{r^2}dr = \frac{Gm_1m_2}{r}\Big|_{r=r_1}^{r_2}$$

- Letting $U=0$ at $r=\infty$ we get that: $\boxed{U = -\frac{Gm_1m_2}{r}}$

$$\Delta U = \frac{GMm}{R} - \frac{GMm}{R+h} = \frac{GM}{R}m\left(1-\frac{R}{R+h}\right)$$

Taylor expand $= \frac{GM}{R}m\left(1-\left(1-\frac{h}{R}+\frac{h^2}{R^2}-\frac{h^3}{R^3}+\dots\right)\right) \approx \overset{g}{\boxed{\frac{GM}{R^2}}}mh$

- Total Potential Energy $= U_T = \sum_{i\neq j}^{n} U_{ij}$

Orbits of Satellites

- Consider body m travelling around body M $m \ll M$

$\boxed{E_T = K + U = \frac{1}{2}mv^2 - \frac{GMm}{r}}$ $E<0$: Gravitationally bound; $E \geq 0$: unbound

- Escape velocity: $E = 0$
- Assume circular orbits. Then:

$$F_{centripetal} = F_{gravitational}$$

$$\frac{\cancel{m}v^2}{\cancel{r}} = \frac{GmM}{r^{\cancel{2}}} \Rightarrow \boxed{v^2 = \frac{GM}{r}}$$

Energy of Circular orbit: $E = \frac{mv^2}{2} - \frac{GmM}{r}$

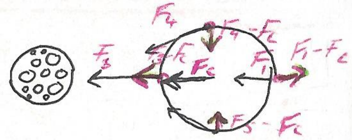
$E = \frac{1}{2}\frac{mMG}{r} - \frac{GmM}{r} = \boxed{-\frac{1}{2}\frac{GmM}{r}}$ $E<0$ Bounded

Period of orbit:

$v = \sqrt{\frac{GM}{r}}$ & $\frac{2\pi r}{v} = P \Rightarrow \boxed{P^2 = \frac{4\pi^2 r^3}{(\sqrt{GM})^2}}$

Tides

- Gravitational force depends on displacement
- Earth is not a point, so different parts ~~have~~ feel different gravitational force from Moon



$$\Delta F_{TID} = F_g(r+\Delta r) - F_g(r) = \frac{F_g(r+\Delta r) - F_g(r)}{\Delta r}\Delta r$$

$$\boxed{\Delta F_{TID} \approx \frac{dF_g}{dr}\Delta r = -\frac{2GMm\Delta r}{r^3}}$$

Tidal Locking

1. Earth does not respond instantly to tidal effects
   → Earth's rotation causes a bulge
2. Moon's gravity pulls back misaligned bulge
3. Slower rotating Earth ⇒ Moon's distance increases
   → Because total angular momentum is same

- Tides can also cause heating (E.G: Jupiter's moon Io)
  - Jupiter has a very large mass
  - Eliptical orbit causes small tidal bulges

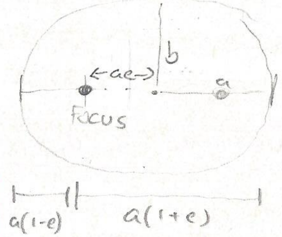
Kepler's Laws of Orbits

1. Planetary orbits are ellipses, w/ the sun at one focus — $\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$
2. Planets sweep out equal areas in equal times in orbits — $r \cdot v = r^2\omega = $ constant
3. Period^2 ∝ Semi-Major Axis^3 in an orbit — $T^2 \propto \frac{4\pi^2}{GM}r^3$

Ellipse: $\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$ Eccentricity: $e = \sqrt{1-\frac{b^2}{a^2}}$

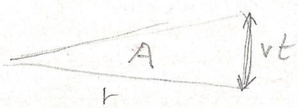
(Polar): $\frac{a(1-e^2)}{r} = 1 + e\cos\theta$

a = semimajor axis b = semi-minor axis



- Second law demonstration:

$A = r\cdot vt \Rightarrow \Delta A = r\cdot r\frac{d\theta}{dt}\Delta t \Rightarrow \boxed{\frac{dA}{dt} = r^2\frac{d\theta}{dt}}$



But: angular momentum is constant

$L = \cancel{d}r\times p = mv_\perp r = $ constant

$= m(r\frac{d\theta}{dt})r = mr^2\frac{d\theta}{dt} = $ constant ☐

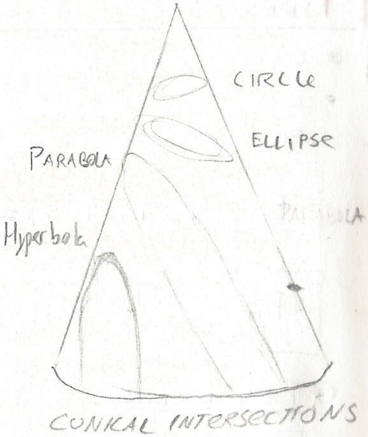
Kepler's Laws: Extended

Newton: ① Kepler's Laws apply to all orbiting bodies

② Ellipses are not the only orbital path:

Bound
- Circles: $e = 0$
- Ellipses: $0 < e < 1$

Unbound
- Parabola: $e = 1$
- Hyperbola: $1 < 1$



③ Objects orbit common Centre-of-Mass

Period $P^2 = \dfrac{4\pi^2}{G(M_1+M_2)} a^3$

$$\text{Period}^2 = \frac{4\pi^2}{G(M_1+M_2)} a^3$$

Demonstration:

$$F_1 = m_1\omega^2 r_1 = m_1\left(\frac{2\pi}{P}\right)^2 r_1 = \frac{GM_1M_2}{d^2}$$

$$F_2 = m_2\omega^2 r_2 = m_2\left(\frac{2\pi^2}{P}\right)^2 r_2 = \frac{GM_1M_2}{d^2}$$

$$\Rightarrow r_1 = \frac{Gm_2}{d^2}\left(\frac{P^2}{4\pi^2}\right) \qquad r_2 = \frac{Gm_1}{d^2}\left(\frac{P^2}{4\pi^2}\right)$$

$$\Rightarrow r_1 + r_2 = d = \frac{GP^2}{4d^2\pi^2}(m_1+m_2) \Rightarrow \boxed{P^2 = \frac{4\pi^2}{G(m_1+m_2)} d^3} \blacksquare$$

Orbital Energy

- $E = K + U = \frac{1}{2}mV_{orb}^2 - \frac{GMm}{r} = \text{constant}$

For Circular: $V_{orb}^2 = \frac{GM}{r} \Rightarrow E = \frac{1}{2}m\left(\frac{GM}{R}\right) - \frac{GMm}{R} = \frac{GMm}{2R}$

For Ellipse: $V_{orb}^2 = \frac{2GM}{r} - \frac{GM}{a} \Rightarrow E = \frac{GMm}{r} - \frac{GMm}{2a} + \frac{GMm}{R} = \frac{GMm}{2a}$

- Escape Velocity: $E = 0 \Rightarrow K = U \Rightarrow \frac{1}{2}mv^2 = \frac{GMm}{r} \Rightarrow \boxed{V = \sqrt{\frac{2GM}{r}}}$

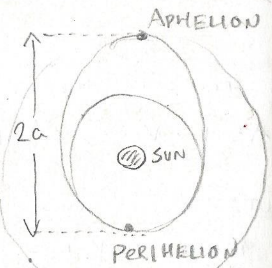
$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

- Lose Energy: ① Gravitational interactions w/ other bodies
  ② Atmospheric drag

Travelling through Solar System

- Flyby = fly by another world once
- Orbiter = go into orbit around another world
- Probe/Lander = land on surface
- Sample Return Mission = bring back samples to Earth

- Change energy to orbit another body into ellipse orbit: $\boxed{E = -GMm/2a}$



Inner Planets: Earth is Aphelion Outer Planets: Earth is Perihelion

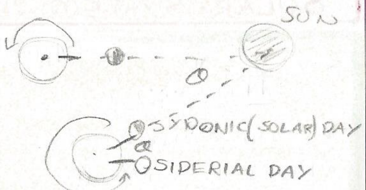
Our Planitary System

Sidereal Day: amount of time it takes the Earth to spin w.r.t. distant stars.

Synodic "Solar" Day: amount of time it takes the Earth to spin once w.r.t the Sun (extra 0.986°)

Sidereal Month: amount of time it takes the Moon to complete one orbit w.r.t. background stars (27.3 days)

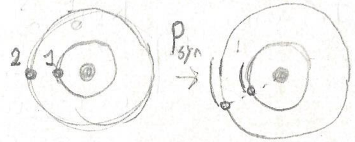
Sydonic Month the amount of time it takes the Moon to repeat its phase → 29.5 days (extra 2.2 days)



$$\theta_d = \frac{360°}{365\,\text{days}} = \boxed{0.986°}$$

$$\theta_m = \frac{360°}{12\,\text{month}} = 30°/\text{month}$$

$$\omega_{rel} = \omega_{syn} = \omega_1 - \omega_2 \Rightarrow \frac{2\pi}{P_{syn}} = \frac{2\pi}{P_1} - \frac{2\pi}{P_2}$$



$$\boxed{\text{Thus, we get: } \frac{1}{P_{syn}} = \frac{1}{P_1} - \frac{1}{P_2}}$$

Example: P_{syn} of Venus $= 1.599$ years

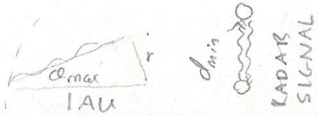
$$\frac{1}{1.599} = \frac{1}{P_r} - 1 \Rightarrow P = 0.61\,\text{yrs}$$

	P_{syn}	P_{sid}
Mercury	0.317	0.241
Venus	1.599	0.615
Mars	2.135	1.881
Jupiter	1.092	11.87
Saturn	1.035	29.46
Uranus	1.012	84.01
Neptune	1.006	164.8

Measuring Inferior Orbits

① Measure largest angle θ_{max} between Sun & planet

→ $d = (1\,\text{AU}) \sin\theta_{max}$ (For Venus: 0.7 AU)



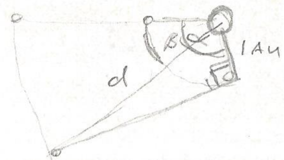
② Measure distance to planet @ closest approach using radar: $(\frac{1}{2})ct = 1 - d$

→ find out what an AU is

Measuring Superior Orbits

① Measure time when both planets align
② Measure time when perpendicular as shown
Δt

$$\beta = \frac{2\pi}{P}\Delta t \qquad \alpha = \frac{2\pi}{1\,\text{yr}}\Delta t \qquad d = \frac{1}{\cos(\alpha - \beta)}\,\text{A.U.}$$



Angular Momentum

$$\vec{L} = \vec{r} \times \vec{p} \rightarrow L = mrv_\perp = mr^2\omega = mr^2\frac{2\pi}{P}$$

$$L_{planet} = L_{rot} + L_{orb} = \frac{2}{5}MR^2\omega_{day} + Mr^2\omega_{year}$$

$$L_{total} = L_{sun} + L_{planets} \approx L_{sun} + \sum L_{orb,planet}$$

→ Gaseous giants have 1% of mass, but 97% of L

Solar-System Inventory

Planets

Terrestrial
- Smaller size & mass
- Dense: Rocks + Metals
- Close to sun, few moons

Jovian
- much larger size & mass
- Low density: H, He, H compounds
- Far from sun & many moons

Rocky Bodies / Icy Comets
- Asteroid Belt
  - most asteroids (Between Mars & Jupiter)
- Kuiper Belt
  - icy objects between 30AU–50AU
  - Eliptical, Neptune at 30AU
- Oort Cloud
  - 50000 AU spherical shell
  - $M_{total} \approx 1\text{-}10 M_e$

- Asteroid = Rocky leftover of planet formation
  - Gap distances due to resonance with Jupiter at $R = \frac{1}{2}, \frac{1}{3}, \ldots R_J$

- Comet = Dirty Snowball
  - Coma = extended region of gas & dust

2 Tails near sun:
- Ion/Plasma Tail: blown straight away by interaction w/ solar wind
- Dust Tail: material left behind in orbit ejected by sunlight preassure
  → dust continues in orbit

Stellar Wind

- Stream of charged particles (ions/electrons) flowing outwards from a star
- Solar wind is partikularly "weak" compared to other types of stellar winds

Meteor: when a meteoroid falls through the Earth's atmosphere & glows & heats up due to friction

Meteorite: meteors that don't burn completelly & hit the ground

- Meteoroids that → meteor often comet tail debris

Physical Properties of Stars

The Electromagnetic Spectrum

- Light can act like either a wave or like a particle.
- Particle of light = a photon

$$c = f\lambda \qquad E = hf \qquad E = \frac{hc}{\lambda}$$

- Different parts of electromagntic spectrum have different names, but there is no limit on possible wavelengths

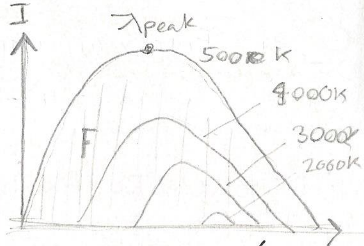
Earth's Atmosphere:
- transparent to visible, near IR, parts of radio
- opaque to all else

Black Body Radiation: Thermal Radiation

Depends (ideally) only on Temperature

(1) Wien's Law: $\lambda_{peak} = \frac{2.9 \times 10^6}{T}$ nm $\left(\lambda \propto \frac{1}{T}\right)$
found by getting derivative of function

(2) Stefan-Boltzman Law: $F = \sigma T^4$ $(\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4})$
F = power per unit area (surface energy flux)
found by getting integral of function

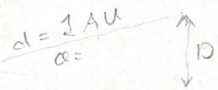


$$\lambda_{peak} = \frac{2.9 \times 10^6 nm}{T}$$

$$Flux = \sigma T^4$$

- Stellar spectrum also shows: dark absorption lines

- Mass of sun derived w/ Kepler's 3rd law
- Size of sun (diameter) found by getting the angular size:



- Solar Temperature:
  $\lambda_{peak} \approx 500nm$, $T = 2.9 \times 10^6 / \lambda_{peak} = 5800K$
- Surface Energy Flux
  $F = \sigma T^4$ = Surface flux
- Power / Luminocity:
  $L_* = F_* \cdot (4\pi R_*^2)$ = surface luminocity

$$L_* = \underbrace{(\sigma T^4)}_{F} \underbrace{(4\pi R_*^2)}_{A}$$

STRUCTURE OF THE SUN

SOLAR WIND: Flow of Charged Particles from surface of sun

CORONA: OUTERMOST LAYER OF SOLAR ATMOSPHERE

CHROMOSPHERE: MIDDLE LAYER OF SOLAR ATMOSPHERE

PHOTOSPHERE: VISIBLE SURFACE OF THE SUN

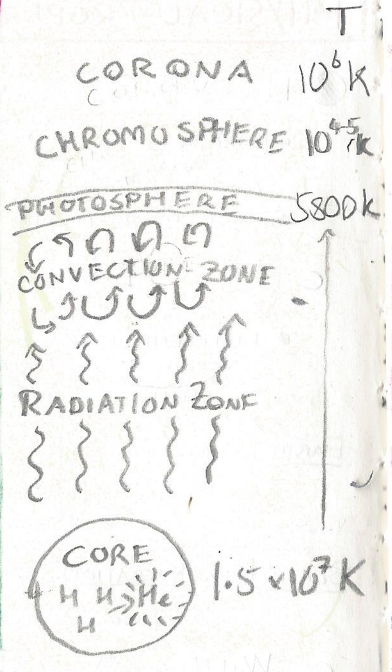
- DARK SPOTS CAUSED BY STRONG MAGNETIC FIELD
- TEMP = 4000K $F_1/F_2 = 4000^4/5800^4 = 0.2$ ⇒ Looks DARKER

CONVECTION ZONE: ENERGY TRANSPORTED UP BY CONVECTION OF HOT GAS

RADIATION ZONE: ENERGY TRANSPORTED UP BY PHOTONS

CORE: ENERGY GENERATED BY NUCLEAR FUSION

- AT T ~ 15 MILLION K $4 \times H \xrightarrow{FUSE} He$ $E = \Delta m c^2$



PHYSICAL PROPERTIES OF STARS

Luminosity = $F \cdot 4\pi R^2$ (where $F = \sigma T^4$)

⇒ Detected Flux = $\dfrac{\text{LUMINOSITY}}{4\pi(\text{distance}^2)} = \dfrac{\sigma T^4 R^2}{\text{distance}^2}$

$$F_{DETECTED} = \frac{L}{4\pi d^2} = \frac{\sigma T^4 R^2}{d^2}$$

SOLAR IRRADIANCE AT EARTH: "SOLAR CONSTANT"

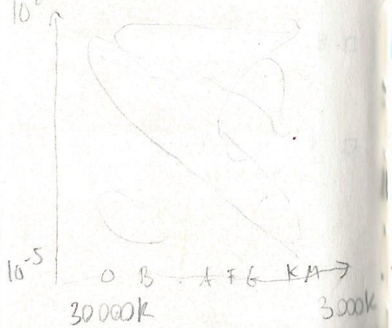
– SOLAR ENERGY PER m^2 ON EARTH ≈ 1350 Wm^{-2}

CALCULATING STELLAR RADII

$$L = \sigma T^4 \, 4\pi R^2 \Rightarrow R = \sqrt{\frac{L}{4\pi\sigma T^4}}$$

STELLAR CLASSIFICATION:

Oh
Boy
A
Fine
G
Kiss
Me



BINARY STAR SYSTEMS

BINARY STARS: stars gravitationally bound to each other

TYPES:

I. VISUAL BINARY STARS

→ VISUALLY see 2 stars orbiting a common Center of Mass

II. ASTROMETRIC BINARIES

→ VISUALLY SEE ONLY THE BIGGER STAR

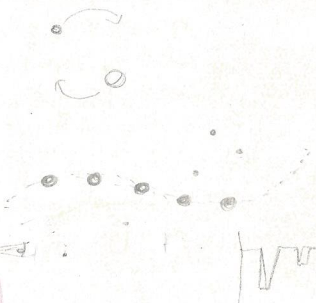
→ WOBBLING C.O.M. ALLOWS US TO INFER PRESENCE OF COMPANION

III. ECLIPSING BINARY

→ ECLIPSING CAUSES PERIODIC DIMMING OF THE STARS

IV. SPECTROSCOPIC BINARY

→ TWO STARS DOPPLER SHIFT IN OPPOSITE DIRECTIONS



DOPPLER EFFECT

- $\Delta\lambda = \lambda - \lambda_0$ THE WAVESHIFT

λ_0 = rest wavelength
λ = observed wavelength

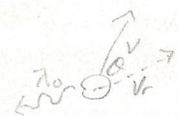
$$\frac{\Delta\lambda}{\lambda_0} \approx \frac{(1+\beta)\lambda_0 - \lambda_0}{\lambda_0} = \beta \approx \frac{V_r}{C}$$

$$\lambda = \sqrt{\frac{1+\beta}{1-\beta}}\,\lambda_0$$

$$\lambda \approx (1+\beta)\lambda_0$$

Ex: $v = 10\,kms^{-1}$, $\theta = 30°$, $\lambda_0 = 6562.8\,Å$

$V_r = V\cos\theta = 8.66\,kms^{-1}$
$c = 3\times10^5\,kms^{-1}$
$\frac{\Delta\lambda}{\lambda_0} = \frac{V_r}{c} = 2.9\times10^{-5}$



- $\Delta\lambda = ?$

$$\frac{\Delta\lambda}{\lambda_0} \approx \frac{V}{C}$$

STAR IN CIRCULAR ORBIT

→ At $t = 0$, $V_r = V$

THIS CHANGES as the star orbits

$V_r = V\cos\theta$

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V_r}{C} = \frac{V\cos\theta}{C} = \frac{V\cos\left(\frac{2\pi}{P}t\right)}{C}$$

- BUT the system could also be tilted at a degree i compared to normal, so

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{C}\cos\left(\frac{2\pi}{P}t\right)\sin(i)$$

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{C}\cos\left(\frac{2\pi t}{P}\right)\sin(i)$$

BINARY STAR ANALYSIS

PERIOD P:
- (i) VISUAL: can measure period of how long an orbit is
- (ii) ASTROMETRIC: see the time for a full wobble
- (iii) ECLIPSING: can see from lightcurve cycle
- (iv) SPECTROSCOPIC: CAN SEE HOW long full cycle takes

ORBIT SIZE R:
- (i) VISUAL: CAN OBSERVE DIRECTLY
- (ii) ASTROMETRIC:
- (iii) ECLIPSING:
- (iv) SPECTROSCOPIC: CAN USE VELOCITIES TO FIND R

$\rightarrow v_1 = \frac{2\pi r_1}{P}$ $\quad v_2 = \frac{2\pi r_2}{P}$ $\quad \Rightarrow r_1 + r_2 = \frac{P(v_1 + v_2)}{2\pi} = R$

MASSES: $\boxed{M_1 + M_2 = \frac{4\pi^2}{G} \frac{R^3}{P^2}}$

WE ALSO KNOW (BY C.O.M.) THAT $M_1 r_1 = M_2 r_2$

$M_1 v_1 = M_2 v_2$

$\frac{M_1}{M_2} = \frac{r_2}{r_1} = \frac{v_2}{v_1}$

so we can also find the mass of each star

- TO FIND ORBIT ~~M~~ MASS, we NEED P & R

MASS LUMINOCITY RELATIONSHIP

- FROM STUDYING MANY BINARY SYSTEMS:

IN the main sequence we observe:

- COOL STARS
  - LOW MASSES
  - LOW LUMINOCITIES

$\longrightarrow$

- HOT STARS
  - HIGH MASSES
  - HIGH LUMINOCITIES

SO WE DERIVE:

MASS-LUMINOCITY RELATION: $\frac{L_*}{L_\odot} = \left[\frac{M_*}{M_\odot}\right]^{3.5}$

MAIN SEQUENCE LIFETIME: $L_* = \frac{E}{t} = \frac{(fM)c^2}{t}$

f is fraction of steller mass converted to energy

$\Rightarrow t = \frac{(fM_*)c^2}{L_*} \Rightarrow \frac{t}{t_\odot} = \frac{M_*}{M_\odot} \frac{L_\odot}{L_*} = \left[\frac{M_*}{M_\odot}\right]^{-2.5}$

- BUT $t_\odot \approx 10^{10}$ YEARS, SO

$t_* = 10^{10} \left[\frac{M_*}{M_\odot}\right]^{-2.5}$ years

TEMPERATURE + LUMINOCITY

$\rightarrow$ MASS-RADIUS RELATION

SOLAR-SYSTEM formation: NEBULAR THEORY

"Solar system formed from the gravitational collapse of a giant interstellar gas cloud."

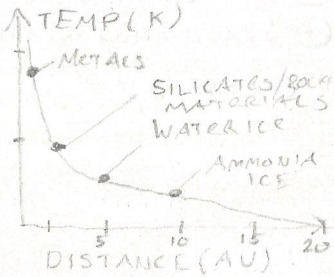
$\rightarrow$ The solar nebula

CLOUD ROTATION $\rightarrow$ DISC $\rightarrow$ PLANET FORMATION

GAS $\xrightarrow{\text{CONDENSATION}}$ TINY PARTICLES $\xrightarrow{F_g}$ PLANETS

- TEMPERATURE in the cloud determines where various materials condense out.

- NEAR $\rightarrow$ HOT $\rightarrow$ METALS CONDENSE $\Rightarrow$ ROCKY PLANET
- FAR $\rightarrow$ COOL $\rightarrow$ "GASES" CONDENSE $\Rightarrow$ GASEOUS PLANETS



FROST LINE: distance at which, once matter cools, water ice could also form

TERRESTRIAL PLANETS: ACCRETION

- small rock & metal particles present inside the frost line
- "Planetesimals" buildup as particles collide
- EVENTUALY these assemble by gravity into planets

JOVIAN (GAS GIANTS)

- SMALL ICE PARTICLES OUTSIDE THE FROST LINE
- LARGER PLANETESIMALS & PLANETS FORM
- GRAVITY DRAWS IN SURROUNDING H and He

THIS EXPLAINS our solar system, but many known ones are different, with GAS GIANTS found within the frost line

$\Rightarrow$ MIGRATE INWARDS DUE TO FRICTION

DETECTING EXOPLANETS

① RADIAL VELOCITY TECHNIQUE

→ PLANET'S GRAVITY CAUSES STAR TO WOBBLE
→ MEASURE THE CHANGING DOPPLER SHIFT
→ ONLY WORKS FOR VERY CLOSE/MASSIVE PLANETS

② TRANSIT METHOD eg: KEPLER, TESS

→ PLANET BLOCKS LIGHT FROM STAR, CAUSING DIMMING OF THE STAR'S LIGHT

DEEPER DIP → LARGER PLANET

WIDER DIP → SLOWER PLANET → FURTHER AWAY

$$\boxed{\text{TRANSIT DEPTH } \Delta F = \frac{R_p^2}{R_*^2}}$$

$$\Delta F = \frac{R_p^2}{R_*^2}$$

③ DIRECT IMAGING
④ GRAVITATIONAL MICROLENSING

} HARD

From the method ②, we can find out the period, & from ① we can find mass, but using the radius, we can also find

$$\text{DENSITY} = \frac{\text{MASS}}{\text{VOLUME}}$$

NAMING

- We put a big letter for stars A, B...
- we put a small letter for planets starting w/ b, c, ...
  → order depends on discovery order

DETECTED PLANET DEMOGRAPHICS

Most exoplanetary systems have:

→ Many very close stars
→ Many large planets
→ Many massive planets
→ Planets w/ high eccentricities

→ Mainly because our detection methods are more sensitive to these kinds of planets

HABITABILITY OF EXOPLANETS

- Basic assumption:
  Life needs liquid water
- We call a planet potentially habitable if it exists in the "Goldilocks zone" where liquid water could exist on a planet

TELESCOPES

Astronomy = observational science

Properties of Telescopes

① Light-Gathering Power: how feint

② Angular Resolution: how much detail

Light Gathering

① Greater Area → more light per unit time

$$\boxed{A = \pi \frac{D^2}{4}}$$

DETECTED FLUX ∝ AREA
"BRIGHTNESS"

② Exposure Time

DETECTED FLUX ∝ EXPOSURE TIME

Angular Resolution

$$\boxed{\Delta\theta = 1.22\frac{\lambda}{D}}$$ Rayleigh Limit (diffraction)

- want larger D
- want smaller λ

LIMITATION: EARTH'S ATMOSPHERE

SEEING: Blurred image due to changing refractive index due to turbulence in air

Typically: max is 1" arcminutes
ideal conditions: 0.3"

SOLUTIONS:
① Telescopes put in space
② Observatories on mountain tops (in deserts)
③ Adaptive Optics (bend mirrors to adjust for distortion)

OBSERVATORY SITES:
- Calm (less turbulence)
- High (less atmosphere)
- Dry (no clouds in the way)
- Dark (no light pollution)

ADAPTIVE OPTICS: shine laser into atmosphere and adjust the shape of mirrors to account for moving lasers → and thus stars

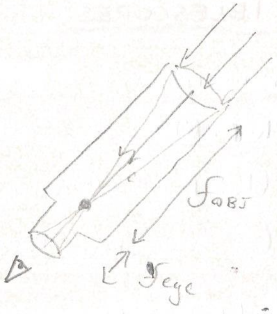
TELESCOPE DESIGN

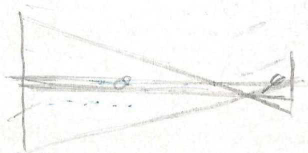
① REFRACTING - FOCUS LIGHT W/ LENS

LIGHT → OBJECTIVE LENS (GREATER LIGHT-GATHERING POWER) → IMAGE AT FOCUS → EYEPIECE (MAGNIFY)

- EYEPIECE ACTS AS magnifying glass for image produced at the focus.

MAGNIFICATION $m = \frac{\phi}{\theta} = \frac{f_{OBJ}}{f_{EYE}}$ ← WANT BIG (f_{OBJ}) ← WANT SMALL (f_{EYE})



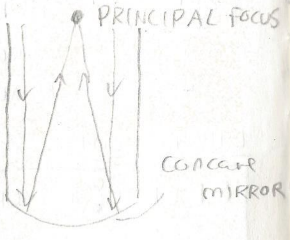


DISADVANTAGES

① LIGHT IS DEFRACTED DIFFERENTLY DEPNDING ON λ
② SOME LIGHT IS ABSORBED BY THE LENS
③ LARGE LENS NEEDED → HEAVY & HARD TO SUSPEND
④ NEED TO BE VERY LONG
⑤ NEED "TWO OPTICALLY ACCEPTABLE SURFACES"

② REFLECTING - FOCUS LIGHT W/ MIRRORS

MIRRORS: GLASS + THIN REFLECTOR (EG: Al) MUST BE ACCURATE WITHIN $\boxed{\lambda/20}$ $\boxed{25\,nm}$



- SOME AREA IS BLOCKED FOR THE FOCUS IMAGE / ITS REFLECTION

ARANGEMENTS

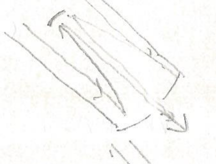
I. NEWTONIAN FOCUS

→ USE MIRROR TO REFLECT THE IMAGE OUT TO THE SIDE

→ DIFFICULT TO USE IN LARGE TELESCOPE AS EYEPIECE AT TOP

II CASSEGRAIN FOCUS

→ USE MIRROR TO REFLECT OUT TO THE BACK



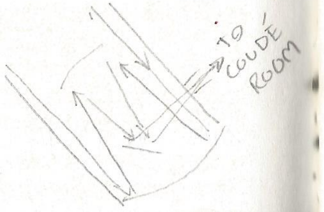
ADVANTAGE: EASY TO USE W/ EQUIPMENT

III COUDÉ FOCUS

→ USE 2 MIRRORS AS SHOWN

→ WHEN EQUIPMENT CANNOT BE EASILY MOUNTED

DISADVANTAGE: LIGHT LOST AT EACH REFLECTION (EG: NEED ROOM W/ TEMPERATURE CONTROL)



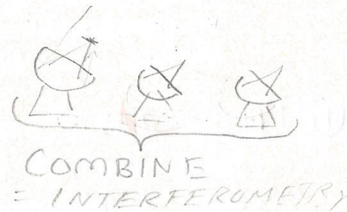
RADIO ASTRONOMY

- λ much BIGGER ⇒ NEED MUCH BIGGER D TOO FOR GOOD RESOLUTION
- SURFACE MUST BE PERFECT WITHIN $\frac{\lambda}{20} \approx 1\,cm$
  → 1 cm holes have no effect

→ CAN BE EITHER CONTINUUM (IMAGES) OR SPECTRUM (SPECTRAL LINE)

INTERFEROMETRY

- USING ARRAYS OF TELESCOPES TO IMPROVE Resolution
  EG: LOFAR



SPACE-BASED OBSERVATORIES

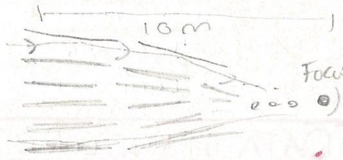
REASONS:
- TO AVOID TURBULANCE → SHARPER IMAGES
- SOME FORMS OF LIGHT DO NOT PASS THROUGH THE EARTH'S ATMOSPHERE

TYPES:

INFRARED - BLOCKED BY ATMOSPHERE
- USED TO SEE THROUGH INTERSTELLER MATTER THAT IS BLOCKING VISIBLE LIGHT

ULTRAVIOLET
- LOOKS AT ULTRAVIOLET RANGE (EG: SUPERNOVA REMINENTS)

X-RAY
- DO NOT REFLECT WELL W/ MIRRORS
- USE SHALLOW ANGLE MIRRORS TO GUIDE
  - GENTLY GUIDED TO FOCUS



GAMMA-RAY
- HIGHEST ENERGY WE CAN DETECT

BEYOND LIGHT:

INTERFEROMETERS TO DETECT GRAVITATIONAL WAVES

OBSERVATION TYPES

I IMAGING = TAKING PICTURES

- Is simply A CAMERA
- FILTER FOR PARTICULAR WAVELENGTHS
- FALSE COLOUR OFTEN USED WHEN ~~RECOMBINING~~ RECOMBINING DIFFERENT WAVELENGTH IMAGES THAT WE CAN'T SEE

II PHOTOMETRY = MEASURING OF LIGHT/FLUX

- measurement of photons
- USED TO CREATE LIGHTCURVES OVERTIME

III SPECTROSCOPY = BREAKING LIGHT INTO SPECTRA...

... WITH ENOUGH DETAIL TO ALLOW STUDY OF SPECTRAL LINES

→ SHOWS CHEMICAL COMPOSITION/MOTION/TEMPERATURE

- DIFFRACTION gratings prefered over prisms
- WANT HIGH SPECTRAL RESOLUTION

RESOLUTION $\equiv \frac{\lambda}{\Delta\lambda}$

- THE MORE LIGHT IS SPREAD, THE MORE TOTAL LIGHT WE NEED TO RECORD SPECTRUM

→ LONG EXPOSURE TIME (MORE THAN IMAGING)

DATA HANDLING (CCDs)

CHARGE COUPLED DEVICES (CCDs)

- RECORD & STORE OBSERVATIONAL DATA
  - CONSIST OF MANY PIXELS
  - CHARGE $\propto$ INTENSITY
  - CHARGE MONITORED ELECTRONICALLY

$$\boxed{\text{QUANTUM EFFICIENCY} = \frac{\#\text{ read out electrons}}{\#\text{ INCIDENT PHOTONS}}}$$

CCDs HAVE QE ~ 75%+ VS. ~5% PHOTOGRAPIC PLATE

→ 10–20 TIMES FEINTER IMAGES DETECTED

- DARK CURRENT: THERMAL EMISSION FROM DETECTOR
  - REDUCE BY COOLING DETECTOR
  - MUST BE SUBTRACTED & PRODUCES ERROR

SIGNAL-NOISE RATIO = ERROR → $\sqrt{N}$ $\qquad \frac{N \pm \sqrt{N}}{T}$

SUMMARY OF FORMULAE

GRAVITATION $\vec{F} = -\frac{GMm}{r^2}\hat{r}$

$$U = -\frac{GMm}{r}$$

ENERGY $E = \frac{1}{2}mv^2 - \frac{GMm}{r}$ → <0 BOUND, → >0 UNBOUND

PERIOD $P^2 = \frac{4\pi^2}{GM}a^3$ as $V^2 = \frac{GM}{r}$

TIDAL FORCE: $\Delta F_{TID} = -\frac{2GMm}{r^3}\Delta r$

KEPLER'S LAWS:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$\frac{dA}{dt} = r \cdot v = r^2\omega = \text{constant}$$

$$T^2 = \frac{4\pi^2}{GM}a^3$$

ESCAPE VELOCITY $V_{esc} = \sqrt{\frac{2GM}{R}}$

$$\boxed{\text{SYDONIC VS. SIDEREAL: } \frac{1}{P_{syd}} = \frac{1}{P_{IN}} - \frac{1}{P_{OUT}}}$$

BLACKBODY RADIATION: $\lambda_{peak} = \frac{2.9\times10^6\,nm}{T}$ WIENS

$\boxed{\sigma = 5.67\times10^{-8}\,W m^{-2} K^{-4}}$ $F = \sigma T^4$ STEFAN-BOLTZMAN

$$L_* = (4\pi R_*^2) \cdot F_*$$

$$F_{DETECTED} = F_0 \frac{R^2}{d^2} \Rightarrow R = \sqrt{\frac{L}{4\pi\sigma T^4}}$$

DOPPLER EFFECT

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{C}\cos\left(\frac{2\pi}{P}t\right)\sin(i)$$

- CAN THUS FIND $M_1 + M_2 = \frac{4\pi^2}{GM}\frac{R^3}{P^2}$

MASS-LUMINOCITY RELATION

$$\frac{L_*}{L_\odot} = \left[\frac{M_*}{M_\odot}\right]^{3.5}$$

→ Lifetime of star $= t_\odot\, 10^{10}\left[\frac{M_*}{M_\odot}\right]^{-2.5}$ years

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

ATMOSPHERE: $\Delta\theta_{max} \approx 0.3 - 1''$

MAGNIFY (LENS): $\frac{f_{OBJ}}{f_{eye}}$ $\qquad$ MIRROR ACCURACY: $\frac{\lambda}{20}$