Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune

1 A.U.

Rocky

Snow line: cold enough volatile components to condense into ice grains ~3 AU

- Sun: O_2, N_2, He
- Mercury: smallest, thin atmosphere, mag field 1% Earth, water ice poles
- Venus: retrograde spin, thick atmosphere, greenhouse effect, volcanism & tectonics
- Earth: CO_2, clouds sulfuric acid, 78% N_2, 21% O_2, 1% other, magnetosphere
- Mars: 1/2 size earth, thin atmosph, CO_2, N_2, Ar, great red spot, no magnetosphere
- Jupiter: 11 × earth, H_2, He, atmosph, magnetosphere, winds 350 m/s, dense metal core, 16–54 × Earth's
- Saturn: 9 × earth, H_2, He, atmosph, H_2O, CH_4 (blue), 10 × Saturn diameter, rings mostly water
- Uranus: 4 × earth, H_2, He, atmosph, ammonia, huge winds
- Neptune: small rocky core, Bath 1781

Mass variation: inertia contributed

$$I = \int dI = \int_0^r r^2\, dm$$

- solid sphere: $I = \frac{2}{5} MA^2$
- hollow sphere: $I = \frac{2}{3} Mr^2$

Layers: temp grad with altitude
Reg's: fixed temp

Yarkovsky effect: solar rad on small body carries off momentum & heat

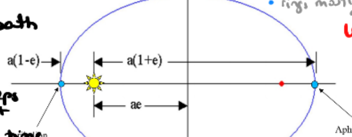
Newton's laws

1) rest unless external F
2) $F = ma$
3) Act° = React°

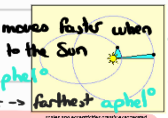
Kepler's Laws

1) Each planet's path around sun ellipse (at one focus)
2) Line to sun sweeps equal distance at all interval of time
3) $\frac{a^3}{T^2} = \text{cnst}$

Earth: $a = 1\text{AU}$, $T = 1$ year



Planet moves faster when closer to the Sun
perihelion
slower → farthest aphelion



$$\frac{dA}{dt} = \frac{1}{2} r^2 \frac{d\theta}{dt} = \text{cnst}$$

a = size of orbit (semi-major axis)
e = eccentricity
θ = polar angle (0 at perihelion, +π at aphelion)
r = heliocentric distance

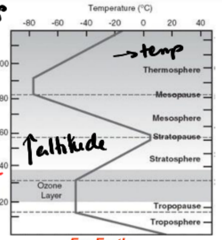
$$r = a \times \frac{(1-e^2)}{(1+e\cos\theta)}$$

TWO WAY TRAVEL TIME $\Delta t = \frac{2d}{\text{speed}}$ ≈ ns / du

Wien's displacement Law

$$\lambda_{peak} = \frac{b}{T} \leftarrow \text{cnst of prop} = 2.9 \times 10^{-3}$$

$$\frac{T}{\nu_{max}} = 0.5099\ (\text{mK})\quad 2898\ \mu\text{mK}$$



ATMOSPHERE

Photodissociation and ionisation of CO_2

CO_2 radiative cooling

Ozone absorption

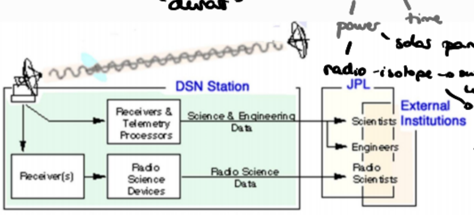
Weather, clouds etc.

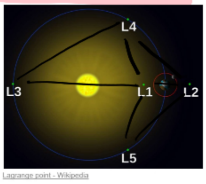
Dark surfaces absorb heat
clouds reflect rad
climate change is expanding the tropical cells which pushes high-altitude clouds poleward

MISSION DESIGN

- targets: planetary syst, orbiting/landing, local conditions
- instruments → needs task
- duration

power — time
solar panels
radio-isotope → output ↓ with time, useful for away from sun





Lagrange point - Wikipedia

Lagrange points are good for satellites (need for "halo orbits" around L_{1-3}). They are also good for natural objects.

In the Sun-Earth system:

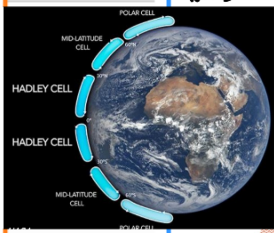
L_1 (1.5 × 10^6 km from Earth, 0.01 AU) Solar and Heliospheric Observatory (SOHO) Other solar observation satellites

L_2 (same as L_1) Herschel Space Telescope (2009-2013) James Webb Space Telescope (tbc) Good for stable temperature (50 K)

L_3 Unstable point but space-weather satellites planned (halo orbit, 7-day warning of solar eruptions)

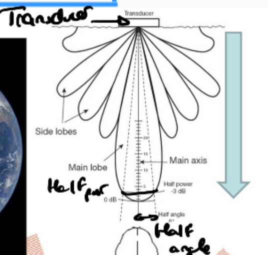
L_4 and L_5 Interplanetary dust, "trojan" asteroid

Closer to the Earth: need to account for gravitational field of the Moon



Beam cones

Trans Transducer



Half pwr
Half angle

DSN (Deep-Space Network)

Typical radio power: 20 W (e.g. for Voyager)

Typical bandwidth: 100's kilobits/second

Several nodes: accounts for Earth rotation

minus rate temp change with altitude with descent

assist vertical mot°	unstable atm	$\Gamma_{env} > \Gamma_{air}$
doesn't assist or resist	neutral atm	$\Gamma_{env} = \Gamma_{air}$
resist vertical mot°	stable atm	$\Gamma_{env} < \Gamma_{air}$

Lapse rate = rate of descent

Case vertical stab

$$\Gamma_d = -\frac{\partial T}{\partial z} = \frac{g}{c_p}$$

$$\Gamma_{sat} = \Gamma_d + \left(\frac{\Delta H_m}{c_p} \times \frac{\partial w_m}{\partial z}\right)$$

diff rising air lapse rate with env

ΔH_m = evaporat° heat

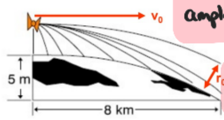
w_m = mass fract° of water vapour

Orbital mechanics

amplitude ascend: $\frac{v_i^2}{r_0}$

gravity: mass × centripetal

$$G\frac{mM}{r_0^2} = m\frac{v_i^2}{r}$$

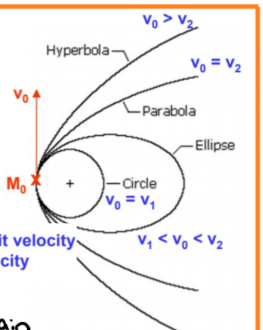


Different orbits for different parts of the mission

Example: Psyche (2023 – 2030)

$$\therefore v_1 = \sqrt{\frac{GM}{r_0}}$$

$$v_2 = \sqrt{\frac{2GM}{r_0}}$$



v_1 = circular orbit velocity
v_2 = escape velocity

Approach: (100 days)

- Optical navigation and instrument calibration, hazard assessment
- Psyche spin axis and rotation period determination

Orbit A: Characterization: 40 days (29 orbits)

- Nadir mapping for preliminary shape determination, global color mapping, magnetic field detection, and gravity science

Orbit B: Topography: 50 days (90 orbits)

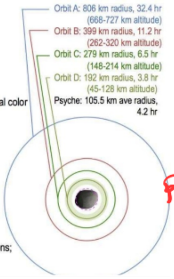
- Nadir and 4 off-nadir imaging cycles for topography
- Global color maps, gravity science, and preliminary magnetic field characterization

Orbit C: Gravity Science: 100 days (369 orbits)

- Gravity science, magnetic field mapping, crater age determination, and preliminary neutron mapping

Orbit D: Elemental Mapping: 70 days (442 orbits)

- Map elemental composition with gamma rays and neutrons; improved imaging, gravity, and magnetic field mapping



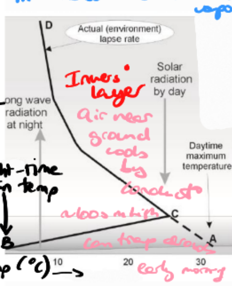
Hydrostatic eqm

$$dp = -\rho_d\, g\, dz$$

with altitude: $-\partial T/\partial z$

dry air: $R_d = 287\ \text{J kg}^{-1}\text{K}^{-1}$

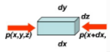
$$\frac{dp}{p} = \frac{-g}{R_d T}\, dz \Rightarrow p(z) = p(0)e^{\dots}$$



Invers° layer: air near ground cools by conduct° allows ... early morning
Night-time min temp
Temp (°C)

Pressure gradient along x direction:

$$F_x = p(x,y,z)dydz - p(x+dx,y,z)dydz$$
$$= p(x,y,z)dydz - \left(p(x,y,z) + \frac{\partial p}{\partial x}dx\right)dydz$$
$$= -\frac{\partial p}{\partial x}dV$$



In 3 dimensions: $F_p = -\nabla p\, dV$

Adding the Coriolis force: $\frac{du}{dt}\rho\, dV = -\nabla p\, dV - 2\sin\beta\Omega(k \times u)\rho\, dV$

(equation of motion for the elemental volume)

Roughness terrain

Lo average height

$$\bar{h} = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} z_{i,j}$$

Lo rms roughness

$$h_0 = \frac{1}{N^2-1}\sum_{i=1}^{N}\sum_{j=1}^{N}(z_{ij} - \bar{h})^2$$

Lo rms tilt

$$s_0 = \frac{\sqrt{\langle[z(x) - z(x+\Delta x)]^2\rangle}}{\Delta x}$$

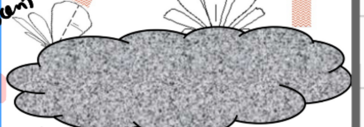
Cloud format°

unstable atmosphere ⇓ condense out of rising air (local humidity 100%) cloud format°

Lifting Condensat° level

*Condensat°: water droplets nucleate on aerosol particles, will fall down at terminal velocity

wind shear: difference in wind speed btw neighbouring layers: shear vector



$$\frac{K \times u_g}{T} = -\frac{R_d}{\dots}\,\Omega\, h\, p$$

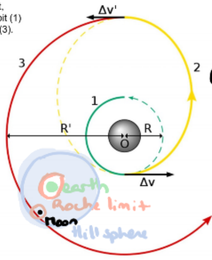
$$\frac{\partial}{\partial z}\left(\frac{K \times u_g}{T}\right) = \frac{g}{f}\,\frac{1}{T}\dots = \frac{g}{fT^2}\,\nabla T$$

Changing Orbits

Hohmann transfer orbit: part of elliptic orbit, between initial orbit (1) and desired orbit (3).

Transfer (2): changing velocity/direction by firing thruster(s) at beginning and end (to make new orbit circular).

Used to move between orbits or for orbit insertion



$$d_{Roche} = A\left(2\frac{M}{m}\right)^{1/3}$$

= Boom

$$d_{Hill} = A \times \sqrt[3]{\frac{m}{3M}}$$

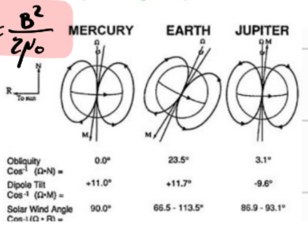
sphere = primary, grav = bis body

earth, Roche limit, Moon, Hill sphere

Heliosphere: magnetic lines of force from the ecliptic plane

$$\text{Mag pressure: } p = \frac{B^2}{2\mu_0}$$

Rotation of planet (i.e. (non?)-conducting body + influences shape of magnetosphere.

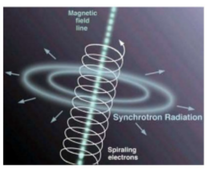


Synchrotron emiss°

Charged particles spiralling around magnetic field lines, close to c.

Particles (usually e⁻) always change direction, emitting photons with frequencies determined by speed at emission.

Resulting radiation confined to a narrow cone, pointing in the direction of motion (*beaming*). Polarised in plane perpendicular to magnetic field.



Particles of mass *m* and charge *q* moving perpendicular to the uniform magnetic field *B* emit at the cyclotron frequency:

$$f = \frac{qB}{2\pi m}$$

Synchrotron emission: mostly radio, but can also occur at visible, UV and X wavelengths.

Plasma frequency

Ionosphere reflects radio waves with frequencies up to plasma frequency ω_p

$$f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{\epsilon_0 m_e}}$$

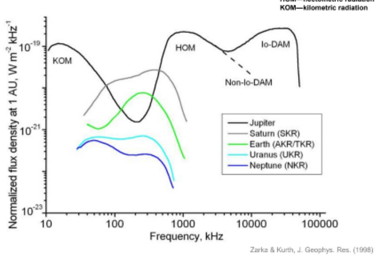
N = number of electrons (charge *e*, mass m_e)

The plasma frequency is the frequency at which the electrons in the plasma naturally oscillate relative to the ions.

Typically 2 – 20 MHz for conditions in Earth's ionosphere.

3.2. Radio emissions

Planets have their own radio emissions



Zarka & Kurth, J. Geophys. Res. (1998)

Planet Format°

can only form out of cold gas
competit° gravity & internal pressure
stars form when gravity beats internal pressure

① Virial thm $K = \frac{1}{2}U$

$$K = N\frac{3}{2}k_B T \quad \& \quad U = -\frac{3}{5}\frac{GM^2}{R}$$

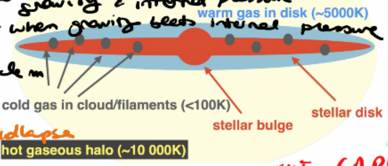
M = mass of the cloud = N × mass each particle m

$$\therefore N = \frac{M}{m} \quad \therefore 3Nk_BT = \frac{3}{5}\frac{GM^2}{R} : \text{eq}^m$$

If $3Nk_BT < \frac{3}{5}\frac{GM^2}{R}$: gravity wins → collapse

$$M_{Jeans} = \left(\frac{5k_BT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

when $M > M_{Jeans}$: cloud collapse



② angular momentum never 0
as collapse proceeds: R↓: rotational v↑
materials move towards centre, angular momentum moves outwards = Accret°
lighter gas particle move centre, leaving disk dust grains

M_{disk} ∝ M_*: cnst proportionality 0.002 – 0.006

where planets form

$\Sigma M_p \ll M_{disk}$

Disk lifetime: 3 – 10 Myr

Once ⭐ 'switches on' radiat° pressure → evaporates remaining disk

Gravitational collapse (faster) PLANETS FORM → Core accret° assembly from smaller clumps

$$Q = \frac{c_{sound}\,\kappa}{\pi G\,\Sigma}$$ ← freq, density

$$R_{Bondi} = \frac{GM_p}{c_{sound}^2}$$ ← rad for atmosph

$$R_{Hill} = a\left(\frac{M_p}{3M_*}\right)^{1/3}$$ ← rad of grav attract°

Toomre param: Q = 1 stable: good to the collapse

THE CARRINGTON EVENT

Powerful geomagnetic storm, 1-2 September 1859. Largest on record. Preceded by CME observed by Carrington and by Hodgson

Polar aurorae were so bright that in some places they were mistaken for the rising sun ("brighter than the full moon" according to some newspapers)

They extended to much lower latitudes (e.g. Colombia).

Estimated to be ~ 800 nT to ~1,750 nT (compared to Earth's field of 25,000 – 65,000 nT and interplanetary field of 4 nT)

Telegraph disruptions: from electric shocks to sparks and even fires.

A similar event happening now (when we use more electricity-dependent tools) would cost roughly 3.6% to 15.5% of annual GDP. In the US alone.

Lesser events occurred for example in 1989 ("Québec power blackout", twice smaller), and might have happened earlier too, e.g. in 1770 (Hayakawa et al., Astrophys. J. Letters, 2017)

A Carrington-level CME occurred in 2012 (but missed Earth because of the Sun's rotation)

Coherence $E_V^* E_H$

wave propagat° (radar)

$$\nabla^2 \vec{E} = \varepsilon\mu \frac{\partial^2 E}{\partial t^2} + \sigma\mu \frac{\partial E}{\partial t}$$

Solut° form: $\vec{E}(x,t) = A e^{i\omega t} e^{-2\pi i f \sqrt{\varepsilon_r - i\frac{\sigma}{2\pi f}}}$

Horizontal & vertical components: $A = A_H e^{i\delta_H} + A_V e^{i\delta_V}$

$\varepsilon \mu^2 c = 1$

cplx permittivity: $\varepsilon - i\frac{\sigma}{2\pi f}$

dielectric cnst: $\varepsilon_r = \frac{1}{\varepsilon_0}\left(\varepsilon - i\frac{\sigma}{2\pi f}\right)$

i.e. cplx relative permittivity

skin depth: $2\times$ penetrat° depth

declines with decreasing tem

Power: strength integrated over 1 period

$E = h\nu = \Delta E$ $\quad \lambda_{max} \times T = 2898\,\mu m\cdot K$

$\lambda = \frac{c}{f}$

Distance btw two waves

Fractals: allow quantify variat° height/slope with the horizontal measurement scale

FT - deconvolving image

water $z \simeq 2.15$

Albedo: how reflective a target is at a particular wavelength

albedo $\not\propto$ dielectric cnst.

but related ? albedo can result from either

- → large surface roughness
- → very dense surface composed of rock
- → porous metallic surface
- → ...

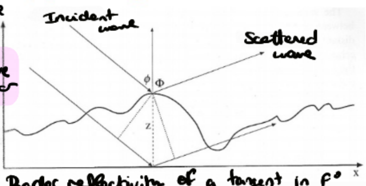
loss tangent $\tan\delta = \frac{\sigma}{2\pi f \varepsilon}$

$10\log_{10}(A_1/A_2) = \Delta A$ (dB)

Snell's Law

transmitted wave: $\theta = \sin^{-1}\left(\sin\phi \frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}}\right)$

Propagation through 2 media



Radar reflectivity of a target in $f°$

Power transmitted P_t W/m²

backscatter coeff σ_0 [ ]

Power received P_r W/m²

directive gain of antenna G [ ]

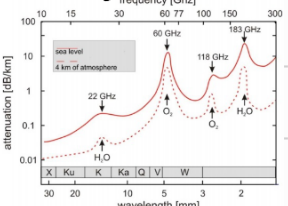
distance R [m]

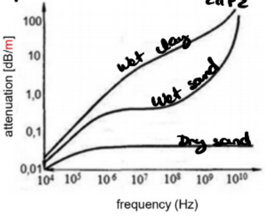
Radar eqt°

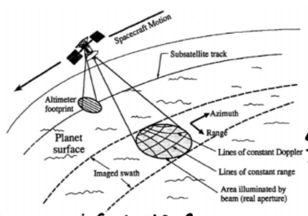
$$P_r = P_t\, \sigma_0\, A \frac{G^2 \lambda^2}{64 R^2 \pi^3} \;[W/m^2]$$

reflectivity

5.1. Magellan radar mapping







Radar scattering

impossible to solve analytically $L_c > \lambda$

$\frac{L^2}{h_0} > 3\lambda$ correlat° length

Kirchhoff → physical optics

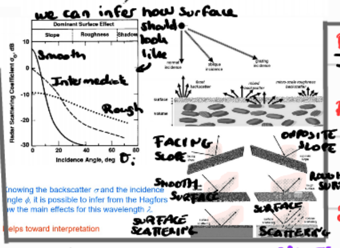
$E_s \ll 1$: phase f_j → ray optics

geometric optics

Mixing material diff prop

- Lichteneker formula: $\log\varepsilon = V_1\log\varepsilon_1 + V_2\log\varepsilon_2$
- Lorentz-Lorentz formula: $\frac{\varepsilon-1}{\varepsilon+2} = \sum_{i=1}^{n} V_n \frac{\varepsilon_n - 1}{\varepsilon_n + 2}$ (n-component mixture)

we can infer how surface looks like



Knowing the backscatter σ and the incidence angle θ, it is possible to infer from the Hagfors law the main effects for this wavelength λ.

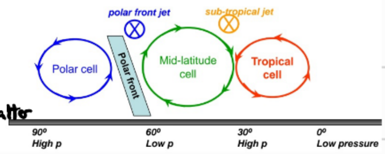
helps toward interpretation

General circulat°: horizontal movements created by pressure diff

Horizontal movements created by pressure differences (i.e. wind)

Large scale circulation:

- Intense solar heating near equator.
- Warm air rises and cools, moves polewards and goes down again — *subtropical high pressure regions*
- Spreads out toward equator and poles
- Air moving poleward will meet colder polar air — *subpolar low pressure belt*
- Polar air mass rises and returns to the pole



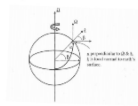
Driving Forces

A volume dV of air, with mass ρdV and velocity **u**, will feel forces:

$$\rho\, dV \frac{du}{dt} = F_{Pressure} + F_{Coriolis}$$

Viscous drag forces (from neighbouring layers of air at different velocities) are negligible above 500 m (because of small vertical gradient of wind velocity)

Coriolis force F_c arises from rotation of the Earth:

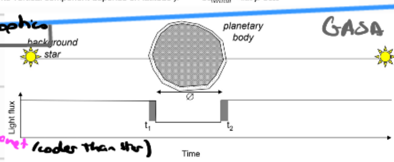


$F_c = -2m(\Omega \times u)$

Ω = angular velocity of rotating reference frame

$F_c = -2\rho dV \sin\beta\, \Omega(k \times u)$

Its vertical component depends on latitude β $\quad \Omega_{vertical} = \sin\beta\, \Omega k$



GAIA

Planck's law - stars

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Rayleigh-Jeans approx - planet (colder than star)

$$I(\lambda, T) = \frac{2ck_B T}{\lambda^4}$$

$I \propto T \propto A$

Depth secondary transit

$$\Delta F_{2nd} = \left(\frac{R_p}{R_*}\right)^2 \left(\frac{T_p}{T_*}\right)$$

Diameters can be measured:

- directly (angular diameter) — *prone to errors (small values)* — earth & sun: 4×10^{-6}
- with radar — *only for close planets*
- most commonly: stellar occultation — *also reveals planetary atmospheres, wavelength-dependent*

$\varnothing = V \times (t_1 - t_2)$

$\lambda = \frac{c}{f}$

2 diff waves: $10\log_{10}\frac{A_1}{A_2} = \Delta A$ (dB)

$\star$ 101

$0.5\,M_\odot \lesssim \star \lesssim 200\,M_\odot$

→ M_* ~ T_{eff} — we know — measured spectroscopy

$M_* \sim R_*$ $\quad M_* \gg M_p$ $\quad M_* + M_p \approx M_*$

not uniform brightness (star spots)

$\star$ spin around an axis with speeds from $V_{rot} \approx 10 - 200\ km\,s^{-1}$

$V_{rot} \sim M_*$

Kepler's 3rd

$$\frac{a^3}{P^2} = \frac{G(M_* + M_p)}{4\pi^2}$$

Select° effects

Hard — Soft

detectable but rare (environment may swap)

we cannot detect (limit instruments)

completeness correction

TRANSITS ① blocking light ② reflect° ③ reradiat° reflect

Detecting exoplanets

- ① Direct imaging — light reflected surface
- ② Transit — light blocked by planet as it passes from the stars
- ③ Radial velocity — change in spectrum star light as it passes under grav. ⊕
- ④ Astrometry — long term repeated patterns of movement of stars in a series of images
- ⑤ Microlensing — repeated short periods of brightening of stars in series of images due to relativistic effects
- ⑥ Timing variations — anomalies in orbital timings of previously discovered planets that may be caused by as yet undetected planets
- ⑤ Polarimetry — Repeated incidents of polarisat° of the light as light passes through a planetary atmosphere

① Direct imaging

$\theta = \sin\left(\frac{a}{d}\right) \approx \frac{a}{d}$ — angular separat° of planet; semi-major axis; distance from star to us

$\frac{L_p}{L_*} \cdot A \frac{R_p^2}{4a^2}$ $\quad \frac{L_p}{L_*} < 10^{-6}$

- L: luminosity — p: planet, *: star
- A: Bond albedo of planet = fract° light from ✶ that is reflected back, dimensionless $0 \le A \le 1$
- R_p: rad planet

- possibility doing spectroscopy on planetary atmosph to measure temp of planet or even atmospheric composit°
- most sensitive planets R_p, high A, large a (Jupiter type planets)
- unable constrain mass planet

② Transit method

planet passes in front of its star we can measure:

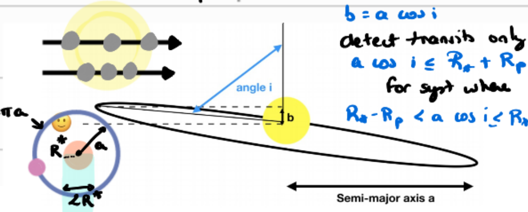
- orbital period planets
- radius of planet
- semi-major axis of orbit $a \approx \left(GM_*\left(\frac{P}{2\pi}\right)^2\right)^{1/3}$

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$ durat° transit → $T_{trans} = P\frac{R_*}{...}$

fractional reduct° in the flux received during the star in the middle of transit

$b = a\cos i$

detect transits only: $a\cos i \le R_* + R_p$ for syst where $R_* - R_p < a\cos i \le R_* + R_p$



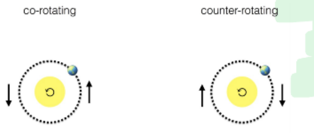
Sketch showing impact parameter b and orbital inclination angle i along with the semi-major axis of orbit a.

Assuming randomly distributed orbital planes $0° \le i \le 90°$, prob planet observed as transit

Prob = no transit orbits / n°all possible orbits

Orbital alignment of exoplanets (see radial for mass & dist)

In the solar system, planets co-rotate with the Sun

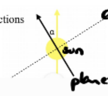


Planets assumed to form from a rotating 'proto-planetary disc' surrounding newly formed star (See later section for planet formation).

In the solar system, the angular momentum vectors of the sun is ~ perpendicular to the planes of orbit of all eight planets. α is the 'spin parameter'.

α ≠ 0 implies past kinematic interactions

Orbital alignment can be measured via the Rossiter-McLaughlin effect



Orbital alignment provides clues to planet formation processes

⑤ Polarimetry

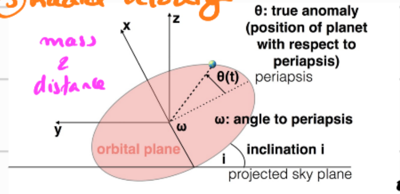
starlight unpolarised: Planetary atmosphere can polarise star light → measure days in polarised over an orbital period: infer presence of planet — VERY DIFFICULT IN PRACTICE

Solar System Outliers? — has light-weight planets, low rad + higher distance from sun, wider orbits & more

M_0: select° effects, radial V: bias to, transit: bias, long orbital period → not an outlier, just harder to see other planets w/ instruments

③ Radial velocity

mass & distance



Sketch showing the radial velocity method of detecting exoplanets

This is a gravitational method

A star and its planet orbit around their common centre of mass.

We can use spectroscopy to detect the 'Doppler wobble' as the star moves back and forth

We will derive the equations of motion for the planet in cartesian coordinates first.

ω = angle of periapsis (the point at which the planet is closest to the star) *wrt* line of sight.

θ = position angle of planet *wrt* periapsis.

The velocities in the x, y, & z directions are v_x, v_y & v_z.

$$v_x = -\frac{2\pi a}{P\sqrt{1-e^2}}\left(\sin(\theta+\omega) + e\sin(\omega)\right)$$

$$v_y = -\frac{\cos i\, 2\pi a}{P\sqrt{1-e^2}}\left(\cos(\theta+\omega) + e\cos(\omega)\right)$$

$$v_z = -\frac{\sin i\, 2\pi a}{P\sqrt{1-e^2}}\left(\cos(\theta+\omega) + e\cos(\omega)\right)$$

i = inclination angle, a = semi-major axis, e = eccentricity, ω and θ as defined above.

We now have the planetary motion in the *astrocentric* (*wrt* star) frame, $\vec{v_{p,*}}$.

$$\vec{v_{p,*}} = \vec{v_p} - \vec{v_*}$$

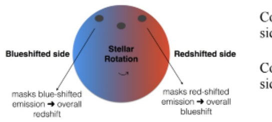
where $\vec{v_p}$ is the velocity of the planet *wrt* the barycentre of the system.

Instrumentat°: astronomical spectroscopes were originally designed to detect doppler shifts due to stellar & galactic velocities [km s⁻¹]

Chapman-Ferraro distance = distance at which planetary field can stand off solar wind pressure

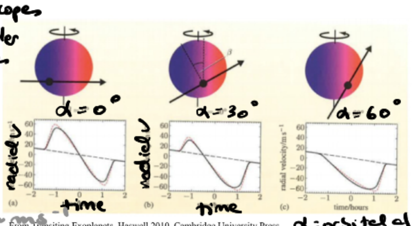
Typical Doppler shifts due to orbiting planet

Orbital alignment of exoplanets: The Rossiter-McLaughlin effect



Co-rotating planets begin transit on blueshifted side, and end on redshifted side.

Counter-rotating planets begin on redshifted side, and end on blueshifted side.



From Transiting Exoplanets, Haswell 2010, Cambridge University Press. Note Haswell uses β for the spin parameter

α: orbital α

We can combine the radial velocity signal due to star orbiting the common CoM of the system with the apparent signal caused by the planet blocking some of the star's light to estimate the spin parameter α.

The RM effect has been measured for several planets. As expected, α ~ 0 in most, But not all cases

The other methods of detecting exoplanets

Astrometry

④ Astrometry

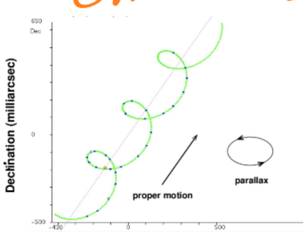


Image thanks to the terrific tools available at the ESA Hipparcos Tools website

Angular displacement of the star from it's CoM

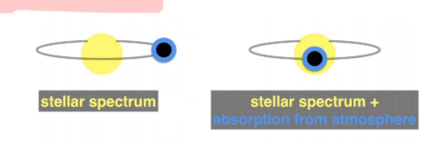
$$\beta = \frac{M_p a_p}{M_* d}$$

Method requires repeated observations of the same region of the sky for an extended period of time.

Selection effect: Angular resolution β < 1 arcsec.

⑥ Transit time variat° previously undetected planets in a system may be found by looking for their gravitational effect on the known planets in the syst → only works if U already found a planet in the syst

Transmission Spectroscopy



While the planet is transiting, it blocks some of the star's light. If the planet has an atmosphere some of the star's light will be absorbed by molecules in the atmosphere.

Therefore, by comparing the spectrum of the star during and between transits, we can detect the presence (or not) of an atmosphere and begin to understand its composition.