Need to know

Given, no info

Given

LECTURE 1: INTRODUCTION

> Planetary Exploration focuses on objects in the Solar System, and explores links to planet formation and exoplanets

↳ Emphasis on science, influence on mission requirements, and generating new knowledge

↳ Done by studying structure, environment, surface characteristics and dynamics

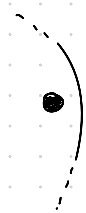
↳ Use of simulations and data (in-situ or remote)

Spacecraft Classification

① Flyby Missions

> Used in initial reconnaissance phase of an object

> Observe targets as they pass by them



↳ Optical instruments need to pan to compensate for motion

↳ Observations are planned ahead of time

- Mercury is hard to orbit, first flyby by Mariner 10, first orbit by MESSENGER
  - ↳ Smallest innermost planet, 2:3 sun:axis spin-orbit resonance
  - ↳ Surface has: ① Scarps or rupes (steep slopes/long cliffs from faults or erosion)
    - ② Thrust faults (breaks in crust, pushing younger rock up)
      - ↳ Reveal global shrinkage of planet (radial: 7 km)

- Triton (Neptunes largest moon), only visited by Voyager 2
  - ↳ Thought to be a dwarf planet from Kuiper belt due to retrograde motion and similarity to Pluto
  - ↳ Has: ① Nitrogen geysers and cryovolcanism forming icy volcanic flows
    - ② Young surface age, possibly from additional heat sources
    - ③ Cantaloupe terrain due to overturning of icy crust

- Plutos orbit is noticably inclined to the ecliptic plane, and has 5 moons
  - ↳ Flyby by New Horizons in 2015
  - ↳ Has: ① Rocky core
    - ② Water-ice mountains

③ Surface of nitrogen ice
④ Traces of methane and carbon dioxide
⑤ Red color from tholins (polymer)

↳ Many processes: ① Cryovolcanism
② wind-related
③ Nitrogen glaciers

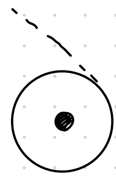
↳ Once had such high atmospheric pressure that nitrogen eroded river patterns

> We can compare seen surface features with those on Earth

② Orbiters

> Second phase of SS exploration, in-depth study of object

↳ Requires propulsion to enter orbit, resistance to frequent solar and Earth occultation (power / thermal / comms limits)



- Venus has a dense atmosphere with high CO_2 content, creating a surface temperature of 735 K

↳ Surface studies done using radar and IR windows

↳ Surface has: ① Volcanic features
② Possibly active volcanism

↳ The atmosphere and resurfacing erased crater records

↳ Old water loss caused a rigid crust, preventing tectonics

↳ ESA Envision and NASA VERITAS upcoming missions

- Saturn has a rock/iron core, pale yellow due to ammonia crystals in the atmosphere, and a density less than water

↳ Rings consist of boulders to dust particles

↳ Flybys by Pioneer 11, Voyagers 1 and 2, orbited by Cassini

↳ Propeller structures are found in the rings caused by small moonlets

- Titan's density suggests half ice, half rock

↳ Atmosphere of methane

↳ Landed on by Huygens, revealed a wet sand-like surface

③ Atmospheric Probes

> Relatively short missions for atmospheric data

↳ No propulsion / ACS required

↳ Does require EPS / TT&C

> Measurements : ① Composition
② Temperature
③ Pressure
④ Density
⑤ Cloud composition
⑥ Lightning

- Pioneer missions on Venus saw no convection between 10-50 km

↳ Below 50 km, temperatures are very similar

↳ Below 30 km, atmosphere quite clear

- Galileo's entry probe returned data for ~1 hour, indicating :

① Intense radiation belt 50k km above Jupiter clouds
② High velocity winds (up to 640 m/s)
③ Less lightning
④ Fewer organic compounds
⑤ Less water vapor
⑥ Half the Helium expected

④ Landed Missions

> Designed to reach the surface and transmit data

↳ Complementary to orbiters

↳ Risky and expensive for great science

- Venera landed on Venus (11/13 successful)

↳ Unique instruments : ① Microphone
② Atmospheric properties
③ Rock drill
④ Penetrometer

↳ Findings : ① Surface mainly volcanic rocks
② Flat layered rocks, indicating cycles of air fall or ground flow
③ Strength less than basalt
④ Internal radiogenic heating similar to Earth

- MASCOT lands on asteroids to measure physical properties and imaging

⑤ Rovers & Aerial Drones

> Subclass of landed missions, able to move over the surface

- Able to move to points of interest
- Requires autonomy due to delay of commands
- Close-up imaging, sampling, sampling return

- Mars is much smaller than expected from formation models
  - Spaceflight mapped surface features such as volcanos, polar ice caps, flowing water, clastic and chemical sediment, dunes, and CO_2 driven processes
  - Many rovers have traveled across Mars

- Dragonfly is a mission designed to fly on Titan as an analogue for early Earth environment
  - Flying ideal due to dense, calm atmosphere with low gravity

The Bigger Picture

> Exploration has given an understanding how planets are shaped by geology

> A Venn-diagram can show overlapping features between various types
  - No body contains all features
  - Unifying hallmark is geological complexity

> The definition of a planet is an ongoing debate (e.g. Pluto)

LECTURE 2: METEORITES

> Asteroids are remnants of the SS formation phase

> Furthermore: ① Meteoroid: in space, 30 μm – 1 m
② Dust: in space, < 30 μm
③ Meteor: light from high speed reentry
④ Metorite: object that survived Meteor phase

> Fireballs are created due to ablating by heating from shock front

↳ Stony objects: fusion crust
↳ iron objects: regmaglypts

↳ Survival depends on material mass, initial speed, and angle

↳ Generally >90% of mass is lost during luminous phase

↳ If flight is aerodynamically stable, ablation happens in an even manner

> Camera networks such as DOERAK exist to detect and locate meteorites

> Asteroids observed before entry are imminent impactors

> The pressure of the atmosphere on a meteoroid:

↳ $P = \frac{1}{2} C_D \rho_g V^2$!

↳ Fracture if $P > \sigma_{max}$. If during luminous phase, a secondary fusion crust is created. If during dark flight, not, and fracture is visible

> Dark flight trajectory is influenced by winds and aerodynamic properties

> The strewn field is the area where fragments end up

> Recovery can happen anywhere, but there are hotspots in Antarctica due to natural ice flow which embeds the fragments, and Chile due to low geomorphic activity

> Recovered: ① 5% Iron
② 1% stony-iron
③ 94% stony

↳ However, composition and features allow for much more detailed classification

↳ This is in relation to the parent body

↳ Achondrites come from differentiated bodies, irons from a core, stony-irons from the transition layer, and chondrites from primitive or metamorphosed asteroids

> Irons show Windmanstätten pattern

↳ Classification based on composition and structure

> Stony are classified using mineralogy and petrology

> Spectroscopy can be used to find the composition of asteroids, and the spectrum is unique for Vesta

Impacts

> Cosmic impacts are collisions of a moving object with a target surface

> The impact cratering depends on kinetic energy transfer:

↳ $E = \frac{1}{2} m V_i^2$

> Crater formation has 3 stages:

① Melting and Vaporization

↳ The surface melts and partially vaporized if $V_i > 12$ km/s

↳ Beyond this, the mass of the melt is:

↳ $M_m = M_p \cdot 0.25 \frac{V_i^2}{\varepsilon_m} \sin\theta$

↳ After milliseconds, melting is over, and energy moves as a shockwave

② Compression and Shockwave

↳ The pressure in the shockwave can be approximated by:

↳ $P = P_0 \left(\frac{a}{r}\right)^3$

↳ The key effect is that rocks at different distances see different pressures

↳ Shatter cones form in the bedrock under an impact crater

③ Excavation and Modification

↳ Material is driven along streamlines, pushing material upward, creating the crater rim

↳ Overturning happens when there is not enough energy to eject material

↳ Inverted stratigraphy

↳ Large, heavy particles move little, small, light move far → ejecta curtain

↳ Two crater states are made:

① Transient crater

- $D_{tc} = 1.161\,(\rho_p/\rho_t)^{1/3}\, L^{0.78}\, v_i^{0.44}\, g^{-0.22}\, \sin^{\frac{1}{3}}\theta$

② Final crater

- $D = 1.17\,\frac{D_{tc}^{1.13}}{D_{s-c}^{0.13}}$

> Secondary hazards include fireball scorching, pressure wounding/fatality, and hurricane force winds

> The transient crater wall can collapse, causing a 60% increase in D

> The amount of impacts follows a power law: $N(>D) = 37\,D^{-2.7}$

> A planetary surface accumulates craters over time, and thus the number of craters per surface area is an indication for surface age

- Also: earlier in the SS, more and larger impacts

LECTURE 4: PLANETOIDS

> Asteroids provide information on planet formation, can represent danger, help understand exoplanetary systems, and could be used for resources

> A planetoid is an astronomical object in orbit of the Sun which is not a planet or a comet

↳ planet which has not cleared its orbit (IAU definition)

Asteroids

> Material in the disk around the Sun condenses as it cools down

↳ Since there are multiple materials, there are different condensation temperatures

↳ From the condensates planets and asteroids formed (gravity)

↳ Some asteroids have not changed much since, and can tell us the age of the SS and composition at begin-of-life of the asteroid

↳ Others did heat up or differentiated, which can explain planetary dynamics

↳ We use dating and classification to reconstruct the SS history

> Asteroids can easily be separated from background stars given long exposure

> Classification is done based on their reflectance spectra representing composition
↳ surface !

1. C — primitive
2. S — stony
3. D and P — more primitive
4. M — metallic
5. V — vesta

↳ S-type dominate in the inner region of the Main Asteroid Belt, M-type in central, and C-type in outer

↳ Shows that temperature decreases with distance from the Sun

↳ NEO has all classes, thus are fed by MAB

> Dating is done using isotopes, which can be unstable

↳ Condensation trapped the isotopes, and "paused" the decay since there is no interaction with an environment

↳ Finding the amount of decay can result in the age of the asteroid

> Decay: ① α : He_2 particle
② β : $n \to p + \beta$ ($\beta^+ : p \to n + \beta^+$) $\beta \approx$ electron, $\beta^+ \approx$ position

> Isotope decay converts a parent isotope into a daughter isotope

↳ $N_p(t) = e^{-(t-t_0)/\tau_m} N_p(t_0)$ ↳ $t_{1/2} = \ln(2)\tau_m$ ↳ $\lambda = \tau_m^{-1}$

↳ $N_d(t) = N_d(t_0) + (N_p(t_0) - N_p(t))$

↳ $N_d(t) = N_d(t_0) + (e^{(t-t_0)/\tau_m} - 1) N_p(t)$

↳ We measure $N_d(t)$ and $N_p(t)$, and know τ_m, but want $(t-t_0)$ and $N_d(t_0)$

↳ Thus, 2 samples are needed from the same asteroid

↳ However, isotopes are not distributed homogeneously, thus we need to normalize using a stable isotope

↳ $\frac{N_d(t)}{N_s} = \frac{N_d(t_0)}{N_s} + (e^{(t-t_0)/\tau_m} - 1) \frac{N_p(t)}{N_s}$

↳ Since we measure two $\frac{N_d(t)}{N_s}$ and $\frac{N_p(t)}{N_s}$, regression results in $\frac{N_d(t_0)}{N_s}$ and $(t-t_0)$

Types

> The MAB is between Mars and Jupiter

↳ The distribution of periods show resonance gaps known as kirkwood gaps

> Ceres is the largest MAB asteroid, the only one rounded by its own gravity

> Dawn: ① Vesta: ⓐ Craters
ⓑ Different minerals using VIR
② Ceres: ⓐ water ice layer under crust
ⓑ Salt crust due to evaporation
} Very different

↳ Vesta closer to terrestrial planets, Ceres possibly formed further away

> Hildas are at 3:2 resonance with Jupiter in an elliptic orbit in a triangular stable configuration

> Trojans are in L4 or L5 of a planet (Jupiter, Uranus, Neptune, Mars, Earth)

> NEA have a short lifetime due to ejection or collision

> OSIRIS-REX sampled Bennu, showing a cohesion-less surface, and materials essential to life

> Shape can be determined of a rotating asteroid by its light curve

↳ Affected by albedo (not constant) and rotation axis alignment

> A body is spherical for a radius larger than:

↳ $R_{min} = \sqrt{\frac{2S}{\pi G \rho^2}}$

- The size distribution can be approximated using a power law:
  - $N(R)\,dR = \frac{N_0}{R_0}\left(\frac{R}{R_0}\right)^{-\xi} dR$ $\xi = 3.5$ from theory in NEO and MAB
- Bodies can collide, potentially leading to erosion or dispersion
- TNOs are classical Kuiper belt objects or scattered disk objects
- Centaurs are between Jupiter and Neptune, thought to have been part of KB earlier
- The Oort Cloud is composed of icy planetesimals

LECTURE 5: OBSERVING PLANETS

- EM from objects can be detected by: ① Photometry
  ② Imaging
  ③ Spectroscopy
  ④ Polarimetry

Light-Matter Interactions

- Interactions: ① Absorption
  ② Emission
  ③ Refraction
  ④ Reflection
  ⑤ Scattering
  ⑥ Fluorescence
  ⑦ Polarization

- The magnitude is a measure for the brightness of objects
  - lower → brighter, higher → dimmer
- The apparent magnitude is the brightness as seen from Earth
  - $m_1 - m_{ref} = -2.5 \log\left(\frac{F_1}{F_{ref}}\right)$
- The absolute magnitude is the brightness at 10 parsec from Earth
  - $m - M = 5\log_{10}(d) - 5$

- Albedo is a measure for the reflectivity
  - $A_\nu = \frac{\text{reflected + Scattered}}{\text{incident}}$
  - $A_b = \int_{\nu_1}^{\nu_2} A_\nu d_\nu$

- The equilibrium temperature is given by
  - $T_{eq} = \left(\frac{1 - A_b}{4\varepsilon \sigma_{SB}} \frac{L_\odot}{4\pi r_p^2}\right)^{1/4}$

- Reflection can be split: ① Specular (perfect flat)
  ② Diffuse (due to roughness)

- The phase angle is the angle Sun-Target-Observer
  - The spectral slope increases with phase angle → phase reddening

- Any reflection induces an increase of linear polarization

- The reflectance spectrum is the convolution of the reflected Solar spectrum with the surface thermal effects

- Electrons sit in discrete energy states

↳ $\Delta E = E_1 - E_0$ ↳ $E = hf = h\frac{c}{\lambda}$

> Interactions depend on phase, and changes the width of spectral features

> Absorption and transmission follow the Beer-Lambert law

↳ $T = \frac{I}{I_0} = e^{-\sigma n L}$ ↳ $N = nL$

Observatories

> Observation performance factors: ① Aperture
② Focal length

> The angular resolution is given by

↳ $R_{angular} = 1.22\frac{\lambda}{D}$

> A low F ratio has more light and a wider view

↳ $F\# = \frac{f}{D}$

> The spectral resolution is

↳ $R = \frac{\lambda}{\Delta\lambda}$

> Filters can be used for specific wavelengths, enhancing contrast, brightness, ...

> Limitations: ① Observability
② Angular resolution
③ Light pollution
④ Artificial satellites
⑤ Atmosphere
⑥ Cultural
⑦ Earthquakes

↳ Solutions: ① Location — high, dry, dark
② Correcting — adaptive optics
③ Space

Spacecraft

much similar stuff as before :)

> Best images are taken up close

> Many constraints, but better/more observations

In-Situ Explorers

> Even more restrictions, but allows interaction with the environment

> Types: ① Fixed
② Mobile

> Landing site needs to be carefully selected

Laboratory Planetary Science

> Used to analyze samples

> Testing and sampling of Earth-based analogue locations

> Lab simulations by artificially creating analogues

> Simpler, cheaper, available

↳ Used to test before space

LECTURE 6: PLANETARY INTERIORS

> SS planets differ (size, density, core size, liquid core)

↳ Interiors of ice giants are poorly understood (common: 3 layer)

> We already have some information through samples and orbiters

> Perseverance made samples ready for pickup to be studied on Earth

> We do not have deep Earth rocks, only meteorite analogues

> Surface provides clues on interior (many craters → not much happening)

↳ Volcanism is driven by interior processes and thus also provides information

Seismology

> From seismic activity on Earth, we know they originate from plate tectonic

> Propagation of seismic waves has shown 3 types: ① Pressure waves
② Shear waves
③ Surface waves

↳ $\rho \frac{Dv}{Dt} = \nabla \cdot \vec{\sigma}$

↳ Seismic waves follow Snells law, experiencing reflection and refraction, and travel in curved paths

↳ Again a critical angle exists at which the refracted wave travels at the surface boundary

↳ Wave velocities:

↳ $V_p = \sqrt{(K + \frac{4}{3}\mu)/\rho}$ ↳ $V_s = \sqrt{\mu/\rho}$ ↳ $V_{rayleigh} = V_s \cdot \frac{0.862 + 1.14v}{1+v}$

↳ Relation between speeds and properties allow for interior models

↳ For an event, there will be the direct, reflected, refracted, and head waves

↳ For some distance further away from the event, the head wave will arrive before the direct wave

↳ S-waves do not propagate in liquids, which can be used to detect the presence of a liquid core

↳ When P-waves hit a boundary, they refract, also making a P-wave shadow zone, allowing the detection of an inner solid core

↳ From seismic activity, the Earths interior could be divided into layers either based on composition or on mechanical properties

↳ From seismic tomography we know the Earth is not 1D either

> Moon seismic events are driven by tides

↳ 2 types of events: ① Shallow
② Deep

↳ We know: ① Small liquid core
② Partial melt above the core
③ Partially solid core from thermodynamics

↳ The core is relatively small compared to Earth (0.14R vs 0.5R), supporting impact theory

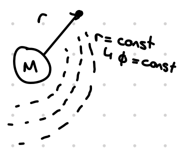
> Mars: ① Liquid core
② Solid core likely

> On icy moons, the ice/ocean interface generates many extra reflections

Gravity

> The gravitational potential of a point mass is

↳ $\phi = -\frac{GM}{r}$



↳ For a given r, there are equipotential surfaces

↳ However, bodies are not point masses or spheres, thus:

↳ $\phi = -G\int_V \frac{\rho}{r}\,dV$

↳ Equipotential surfaces are not necessarily spheres anymore

↳ The gravity field thus tells us about the mass distribution of the body

> Outside the body $\nabla^2\phi = 0$, and we can use spherical harmonics

↳ $\Phi = -\frac{GM}{r}\sum_{l=0}^{\infty}\left(\frac{R}{r}\right)^l \sum_{m=0}^{l} P_{l,m}(\cos\theta)\left[C_{l,m}\cos(m\varphi) + S_{l,m}\sin(m\varphi)\right]$

> From a distribution a ϕ can be found; the inverse is ill-posed

> From $l=0$, the density (average) can be found

> For $(l, m) = (2,0)$: $\phi = -\frac{GM}{r} - \frac{GMR^2}{r^2}C_{2,0}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$, and is related to the flattening of the body

↳ Spin causes a deformation, causing a degree 2 gravity field

↳ The Darwin-Radau approximation relates J_2 to MoI, which can give information about a varying density interior

> Isostasy and topography affect the gravity, and they hide the other effect

> The Moon and Mars have higher correlation between gravity and topology, indicating low internal activity

Time

> Gravity changes over time, e.g. due to: ① Mass transport
② Tidal deformations

Magnetism

> Earth has a dipole magnetic field tilted w.r.t. its rotational axis, caused by convection of iron organized by rotation in the core

↳ $\nabla \times B = \mu J$

> In giant planets, the dynamo is the result of convection of metallic hydrogen

> Mars and the Moon have no dipole magnetic fields, but data suggests they did have dipoles in the past

> Bodies can have an induced magnetic field when we have a conductor experiencing a changing magnetic field

↳ This can be used to detect oceans

LECTURE 7: PLANETARY VOLCANISM

Earth

> Volcanoes typically lie on plate boundaries

> Plate motion determined geologically and geodetically closely agree, despite the wildly different time scales

> Earthquakes can be discriminated by source depth (shallow - intermediate - deep)

> Ocean sea floor bathymetry reveals that hot mantle material wells up at mid-ocean ridges → underwater cracks

↳ upwelling decompressed basalt magmas and hydrothermal vents can be observed, indicating the plates are being pulled apart

① ↳ magma rises from the cracks, cools, and pushes older rock away, creating the oceanic lithosphere

↳ subduction happens as it is pushed under and is heavier

↳ OC - OC subduction causes a trench

② ↳ Subduction causes volcanism (OC / OO convergent plates)

③ > Hot spots are "leaks" within plates causing rising magma, and the 3rd type of volcanism on Earth

↳ 3 types

Moon

> Only partial mantle melting created volcanic rocks

> Smooth Marias are due to flooding by outpouring lava

↳ Closed up due to low viscosity (flow back)

> There is some evidence of explosive volcanism due to small droplets of glass

Mercury

> Some smooth areas are believed to be due to volcanic activity from global contracting due to cooling

Venus

> Basaltic eruptions flooding large areas

> Still active in some spots

> Many coronae, hotspots that became inactive before formation of a shield volcano

- Has pancake domes, large flat domes with steep sides, and lava rivers

Mars

- Features volcanoes larger than Earth

Io

- Most volcanically active in SS, through plumes and lava flows
- Source is tidal friction: internal strain and frictional heating driven

Triton

- Low temperature volcanism: cryovolcanism (water is quite rocky)
- Energy from boiling nitrogen

LECTURE 8: PLANETARY INTERIORS

> Isolated planets in thermal equilibrium would have a spherical shape, but we have rotation, tides, convection, ...

↳ These all cause deformities, giving rise to time changing gravitational coeffs.

↳ $C_{l,m} = C_{l,m}(t)$ ↳ $S_{l,m} = S_{l,m}(t)$

Tides

> Because planets are not points, and thus gravity pulls harder to a closer point

↳ The potential can be computed for any point if we know the distance

↳ $\phi^T = -\frac{GM^*}{c}$

↳ Expressing $\frac{1}{c}$ as a function of the radial distance of the point and the center, body distance, and angle:

↳ $\phi^T = -\frac{GM^*}{d^*} \sum_{l=0}^{\infty} \left(\frac{r}{d^*(t)}\right)^l P_l(\cos(\psi(t)))$; $d^*(t) = f(a^*, e^*, v^*)$; $\psi(t) = f(\Theta, \varphi, i^*, \Omega^*, \omega^*, v^*)$

↳ Looking at tidal curves, we see that many periods are involved, which are related to changes in orbital elements

↳ Considering a static secondary body and a rotating primary, the tide period is half a day

↳ If other way around, period is half of orbital period of secondary

↳ Both happen, and the period is half a lunar day for Earth-Moon

↳ Because the Moon's orbit is inclined, another diurnal component is present

↳ Orbital elements also change over time, causing long periods

↳ We thus have 3 types: ① Semi-diurnal
② Diurnal
③ Long period

> Since the Moon always shows the same face, it has flowed to be an ellipsoid

↳ In a slightly eccentric orbit, bulge changes slightly every orbit

> Tidal forces cause deformations, the amounts depend on internal structure, which is captured by Love numbers

> To compute the tidal response, we solve cons. mass, momentum, poisson, thermo.

> How a planet deforms is a matter of time scale

Moment of Inertia

> J_2 can be measured by spacecraft orbit tracking, which can be used to determine the MoI

> Static tide only depends on density, viscoelastic is sensitive to the mechanical properties

↳ Measuring deformations can tell us about these properties

Rotational Dynamics

> Perturbations affect the rotational state of a planet

> Subsurface oceans cause more libration because the shell is decoupled from the interior

> Typically use conservation of angular momentum

↳ $\frac{dL'}{dt} = T'$ ↳ $L' = I' \cdot \omega$!

↳ Mass redistribution changes revolutionary period

Orbital Perturbations

> A third body causes extra perturbations

↳ Combined with non-spherical effects, interesting things arise

> Mean motion resonances can push the eccentricity, making orbits chaotic

> For viscoelastic bodies, there is some phase lag between tidal force and deformation

↳ $\sin \delta = Q^{-1}$ Q quality factor, related to heat dissipation

↳ Gas giants do not dissipate much heat

↳ Tidal heating:

↳ $\dot{E} = \frac{21}{2} \frac{(nR)^5}{G} \frac{k_2}{Q} e^2$

↳ Affects orbital evolution

↳ If a planet spins faster than a moon orbits, a ΔV is generated and a torque in the primary

↳ If the planet spins slower, the planet spins up, and the moon falls toward it

> we saw that Io is very active due to tidal heating

↳ The energy is coming from the changing orbital energy

↳ causes a decrease in semi-major axis and eccentricity

↳ $e \neq 0$ currently, because MMR increases it

> Orbital and interior evolution are coupled

LECTURE 9: ICY MOONS

Ice and Oceans in Solar System

> Close to the center of the accretion disk it was hot, and metals condensate with no ice

↳ Further away it is cold and ices condensate

↳ Ices form on dust grains via accretion from the gas or evaporation or sublimation

↳ $R_{acc} = n_{gas} V_{gas} \sigma n_{dust} S$

↳ $R_{evap} = n_{ice} v e^{-(E_b/kT)}$

> Snowlines are the transition between gas and ice

↳ $R_{acc} = R_{evap}$

> Besides the 3 main phases, water exists in many types

↳ Different modes within types absorb light at different frequencies

> The presence of an ocean under an icy crust can be determined by:

① Gravity and Tides

↳ The MoI is different for a differentiated body

↳ The shell and interior are decoupled, so the response of the shell to external forces gives information on subsurface oceans

② Magnetic Field

↳ A salty ocean can act as a conducting material, which can induce a magnetic field (Europa is an example)

③ Terrain

↳ Floating icebergs look like chaos terrain, and with similarities to Antarctica a subsurface ocean can be deduced

↳ Gravity anomalies can be explained by subsurface oceans

④ Geysers

↳ Can expel water outwards

Saturn

> Shepherd moons create gaps in the ring system

> Enceladus has an ocean with plumes

↳ Observed temperature does not match predicted, and can not be explained by tidal dissipation and radiogenic heating in the core

↳ The core is porous, and interacts with the ocean:

1. Water influx into core
2. Heating creates plumes interacting with rocks
3. Hotspots are created at seafloor
4. Heat and rock are transported
5. Localized heating thins the shell
6. Plumes erupt

↳ Cassini measured particles and gases in plumes, showing 3 types of material

1. Water ice
2. Organic material
3. Salty material

↳ Imaging and spectroscopy together with greybody radiation are used to determine surface temperature and composition

Jupiter

> Hubble observed H and O emissions from Europa

↳ Galileo data coincided magnetic field changes

> Io is a lava world rich in SO_2 ice

> Europa, Ganymede, Callisto all icy moons with different terrains

> JWST saw CO_2 present on the surface from a subsurface ocean

> JUICE and Europa Clipper investigate this system

Formation of Moons

> Around large planets also an accretion disk formed, forming natural satellites

↳ These can migrate and be lost in the planet

↳ Frozen configuration once gas dissipates

> 3 of Jupiters moons are icy, explained by Jovian snowline

> Saturns rings are ice-rich, indicating that an outer moon likely spiralled in and fractured (possibly into some of current smaller moons)

LECTURE 10: OUTER PLANETS & MOONS

Giant Planets

> Terrestrial planets: ① Iron/nickel core
② Rock (silicates)

> Giant planets: ① Rock
② water
③ Hydrogen (metallic - Molecular gas)

↳ Further away, larger

↳ Cores all roughly same size ~10 $M_\oplus$

↳ Gas captured from solar nebula because the cores were large enough

> All 4 have strong magnetic fields due to rapid rotation and conductive interiors

↳ In Uranus and Neptune, the rotation and magnetic axes are very unaligned

> None have a solid surface, the atmospheres just get warmer and denser

① Jupiter

> Relatively small core 5-10 $M_\oplus$

↳ Inner rocky/iron + outer ice-rich, or homogeneous

> Magnetic field from EM currents in metallic hydrogen region

> Internal heat from gravitational contraction/accretion in the past

② Saturn

> Internal models similar as for Jupiter

> Lower P and T than Jupiter

↳ Still large enough P for metallic hydrogen

> Radiates more energy than received sunlight from gravitational energy of falling He rain

③ Uranus and Neptune

> Similar structures

> Not big enough (not enough P) for metallic hydrogen

> Can have water-ammonia slush

- High density core
- Neptune smaller but heavier
- Mantle 80% of mass, icy composition
- Internal magnetic fields indicate conductive and convective interiors
- Uranus is tilted a lot compared to the other planets

Icy Moons

- 13 bodies in SS have oceans
- For life: ① Energy — tidal dissipation
  ② water — oceans
  ③ Nutrients — from volcanism?
  ④ Time

① Titan

- Titan has a methane cycle analogue to Earths water cycle
- Cassini images revealed hydrocarbon lakes

② Encleadus

- Small but round → low viscosity interior
- Exhibits plumes

③ Europa

- More water than Earth (a lot smaller)
- Cycloides and the combination of the 2 fault types indicate sub surface oceans
- Tidal induced convective motions are hinted at by surface features
- 2 models: ① Thin crust, convecting ocean
  ② Thick convecting crust, thin ocean
- Induced magnetic field reveals subsurface ocean

LECTURE 11: SURFACE GEOLOGY AND PROCESSES

> We use geology to understand how planets are shaped by processes we recognise from Earth

↳ Evolution can inform us about habitability

> Surfaces are shaped by: ① Internal processes — volcanism, tectonics, isostasy
② External processes — glacial, fluvial, aeolian, physical / chemical

↳ Surface is the sum of the two

> Mars is the most Earth-like planet (and can be used as a case study)

> Mineralogy: chemistry, related to formation
> Petrology: what happened since

Internal Processes

> Driven by internal heat, key driver for geologic evolution

↳ Expressed as: ① Magmatism / Volcanism
② Diastrophism (tectonism)

↳ Increase topography and rock formation

① Martian volcano peaks are visible from Earth, peak above the clouds

↳ Mariner 9 discovered calderas (summit depressions), like volcanoes

↳ Columnar jointing is a pattern of fractures in rocks creating hexagonal columns, occurs when lava encounters a cooler surface

↳ Explosive volcanism (bombs) deform horizontal layers, and were imaged by Spirit

↳ Also sorting at Home Plate of grains, indicating hydrovolcanism

↳ Porous (vesicular) basalts in craters and igneous rocks in a fluvial deposit are more indications

External Processes

> Originate from within an atmosphere, driven by energy from the Sun

↳ Dependent on: ① Weather — short term
② Climate — long term

↳ Wears down the variations in relief (gradation)

↳ Endogenic build relief, exogenic evens the surface

> Climate variations are driven by orbital parameters

① Glaciers are formed by self-compaction of snow and gravity driven flows are controlled by internal deformation

↳ Create glacial valleys through erosion, and transports sediments

② Permafrost are extensive water-ice deposits in the subsurface, protected from sublimation by regolith

③ Volcanoes and ice can interact (glaciovolcanism), and can thus be used to infer a surface where both endo- and exogenic processes coexisted

④ Rootless cones form by explosive interactions of lava flows with surface water or permafrost

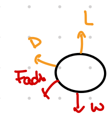
⑤ Wind is a process from larger atmospheric circulation interacting with granular materials at the surface

↳ Many objects do not have the ability for this to happen, but all in SS with an atmosphere do

↳ Aeolian landscapes require windspeeds above a threshold

↳ The boundary layer is smaller as u decreases (and thus flow closer to the surface), making threshold vary with particle size

↳ Wind induced forces need to exceed the resistance



↳ $F_L = C_L \cdot d^2 \cdot \rho \cdot u^2$ ↳ Shear stress τ_{thr}

↳ $F_D = C_D \cdot d^3 \cdot \rho \cdot u^2$

↳ $F_{adh} = C_{adh} \cdot d$

↳ $F_n = \pi \cdot d^3 \cdot g \cdot \rho_{He} / 6$

$$\rho \, u_{*ft}^2 = \frac{F_n + F_{adh}}{F_L + F_D}$$

↳ $\rho = P \cdot \frac{M}{K} \cdot T$

↳ The threshold condition is then found as:

↳ $$\rho \cdot u_{*ft}^2 = \frac{(\pi/6) \cdot g \cdot \rho_p \cdot d^3 + C_{adh} \cdot d}{C_L \cdot d^2 + C_D \cdot d^3}$$

↳ The threshold is V-shaped for varying d

↳ Smaller d: adhesion too strong
↳ Larger d: weight too much

↳ Detachment (roll) happens before entrainment, and the threshold is lowered because of motion and impacting

↳ Grain transport method depends on grain size: ① Creep
② Suspension

③ Saltation

↳ Planetary wind tunnels allow P, T, and composition to be changed to match the surface environment

⑥ Water is constrained to specific T-P conditions, and features thus indicate changing conditions

↳ Domains: ① Rivers (fluvial)
② Lakes (lacustrine)
③ Oceans (marine)

↳ Rainfall delivers water to the surface, and overland flow can occur when the infiltration rate is lower

↳ This can coalesce to streams and downslope channels for porous substrates, which can be deepened by incision and erosion this is a positive feedback loop

↳ Either runoff networks or sapping networks can be created

↳ Alluvial fans form at the end of fluvial channels from sedementary deposit in dry conditions

↳ Deltas are fans where the channels terminate in a lake

⑦ Gravity moving material is mass wasting

↳ Downslope movement of unconsolidated materials on sloping terrain due to gravity

⑧ Physical weathering break rocks into sediments

↳ Primarily due to impacts

⑨ Chemical weathering happens due to liquid water altering minerals comprising rocks

↳ Can tell us conditions, properties, and amount of water on Mars

> The constant change of rocks by exo- and endogenic processes is summarized in the rock cycle

↳ Active when: ① Interior is hot enough to keep the mantle moving
② Surface conditions support liquids and ices cycles

LECTURE 12: SURFACE EVOLUTION & HABITABILITY

> Early observations of global mapping and reconnaissance were limited by instruments and human eyes

> Mapping involves synthesis of instrument data, imagery, and interpretation

> Time is critical for planetary evolution

↳ Techniques exist to derive relative and absolute timelines

> We can apply Earth techniques to understand the sequence of processes on planetary bodies

↳ Stratigraphy is one of these, and has the following principles:

① Superposition
② Original horizontality
③ Cross-cutting relationships
④ Lateral continuity

↳ Initially provide a relative dating of the surface using crater-size frequency distributions $N(>D) = 37D^{-2.7}$

> Valley networks suggest pluvial or fluvial activity

↳ on Mars, indicates that climate at one point differed from what it is now

> Global stratigraphy is constructed by: ① division into units with similar properties
② Ordering using stratigraphic principles
③ Assigning ages (rel and abs) using statistics
④ Compiling into a GIS based global map

↳ 3 regions have been studied from orbit and ground

① Gusev Crater

> From orbit: ① Impact crater size, age, sediment age (crater counting)
② Thought to be ancient lake bed
③ Valley enters has flat hills, thought to be deltas
④ 7 main surface units
⑤ Sedimentary processes or volcanic processes

↳ From ground: ① Volcanic rocks, but no flow, so source: fissure eruptions
② Aeolian features (recent)
③ Sulfate rich soil → hydrothermally active
④ Nothing pointing to lake setting

② Meridiani Planum

> Orbit: ① Layered sedimentary unit in closed basin setting
② Basaltic sandy surface, excavated by erosion

③ Crater hard to date due to erosion and infilling
④ Suggestion to aqueous environment

↳ Ground: ① Aeolian and rock-water interaction structures
② Hematite spherules indicate formation in groundwater

③ Gale Crater

> Orbit: ① 7 main units
② Central peak from cratering uplift process, covered by layers
③ Dating done

↳ Ground: ① Sandstones from delta deposits entering a lake setting
② Gravel from rim was deposited around the peak
③ Transition to sandy deposits mark lake boundary
④ Many sedementary layers exposed due to aeolian erosion

> Mars timeline has 3 main periods:

① Noachian

> No units older are found at the surface

> Large basins form (perhaps from large impact)

> High erosion rates

> Formation of clay-mineral indicates role of water

② Hesperian

> Larger geodiversity due to reduced impacts and lower erosion rates

> Widespread volcanism

> Planetary cooling (seen from wrinkly ridges)

> Formation of catastrophic outflow channels from massive floods

> Change of environmental conditions seen by decline of valley networks

③ Amazonian

> Larger role of wind and ice

> Hematite formation

> Meteorites and lava flows indicate volcanism nearly to present

> Gullies and debris flows most common fluvial features

|> Aeolian processes dominant

> Triaging composition and origins of rocks is done using mineral content and abundance, and context of associations

↳ Diagnostic mineral properties constrain formation conditions

↳ Requires observation of grains within rocks shape, color, ...

↳ Geochemical properties can then be quantified

LECTURE 13: HABITABILITY, ORIGINS OF LIFE & LIFE DETECTION

What is Life

> From astrobiology: an open chemical system capable of self-reproduction

> Living organism should be capable of: ① Homeostasis
② Organization
③ Metabolism
④ Growth
⑤ Adaptation
⑥ Response to stimuli
⑦ Reproduction

Chemistry of Life

> The tree of life is a pattern of relationship that utilizes similarity in genetic coding

↳ Focused on r-RNA as it is strongly conserved

↳ 3 main groups: ① Bacteria: single celled, no organelles and organized nucleus
② Archae: similar, but distinct in cell membrane and genetic coding
③ Eukaryota: cells with nucleus, membrane bound organelles

↳ LUCA is the last common ancestor, population of cells adapted to the early Earth

> Elements are formed through nucleosynthesis in a star

> Life as we know is based on carbon chemistry because it can make complex molecules: ① 4 valence electrons
② Double bonds possible
③ Lysine
④ Proteins

> Nucleotide: nitrogeneous base, sugar, phosphate group

↳ DNA are chains of up to 10^8 nucleotides, involving 10^9 C atoms

> Huge carbon molecules are stable, but remain chemically active and can be broken up

> Amino acids can be left or right handed (chirality)

↳ On Earth, life is left handed

> Enzymes: proteins, essential catalysts, lock and key model, chains of amino acids

> Silicon based life can exist, but low water solubility and unstable in water are problems

> Amino acids contain an amino and carboxylic acid groups, the latter causing the chemical reaction

↳ 20 exist on Earth

↳ Combined form proteins, both are building blocks of life

↳ Formation on Earth happened due to a simple atmosphere with lots of energy from lightning

↳ In space 52 AA have been identified, also some right handed

↳ Formation from simple ice with radiation

Importance of Water

> Besides the building block, we need a liquid solvent

↳ Gaseous has too low density, solid would prevent movement

↳ Water advantages: ① Liquid over wide temperature range
② Large heat capacity → chemical reactions take place without changing T → stable
③ Large dipole moment → increases solubility due to possibility of H-bonds
④ Can react (hydrolysis)

> Earth oceans were formed: ① Wet (from formation)
② Dry: ⓐ Brought by asteroids
ⓑ Brought by comets

↳ ② can be determined by comparing the heavy water ratio in meteorites and oceans

↳ ① from water attached to grains and combining them

> Habitable zone: region around a star where liquid water can exist on the surface of a planet

↳ For a given atmospheric pressure, the zone is a temperature range

↳ $T_p = T_* (1 - A_v)^{1/4} \sqrt{R_* / 2a_p}$; $273 < T_p < 373$ for liquid water

↳ However, this neglects the planet's atmosphere e.g. greenhouse effect

↳ Also, subsurface habitability is a possibility eg. in oceans closer to core

> To look for life in space: ① Changes
② Elements
③ Molecular structures
④ Biomaterial

↳ By use of: ① Mass spectrometer
② IR spectrometer
③ Immunoassay techniques
④ Laser imager
⑤ DNA sequencer

LECTURE 14: MAGNETISM

> Planetary magnetospheres form the largest structure in the SS

> Kepler thought planets had magnetism, and that was their driving force for motion

> Faraday's law of induction: an electric current is created in a wire or electric conductor that moves through a magnetic field

> The Maxwell-Faraday equation

↳ $\nabla \times E = -\frac{\partial B}{\partial t}$ circulation of E around c = rate of change of B through S

↳ $\oint_{\Gamma} E \cdot d\vec{s} = -\frac{\partial}{\partial t} \int_S \vec{B} \cdot \vec{n} \, da$

↳ Change in magnetic flux ($\int B da$) creates an electrical current

> The Lorentz force

↳ $F = q(E + v \times B)$

↳ A force can only come from an electric field or a magnetic field acting on moving charges

↳ The flux rule is valid for any method of changing flux circuit moves vs changing field

Instruments

> Atoms and ions emit radiation which can be seen from Earth

> The magnetic field is a vector field → 3 measured directions required

> A spacecraft creates a magnetic field from its electronica, thus measurements need to take this into account e.g. a boom or rotation

> Dynamic range is quite large → trade accuracy vs wide spread information

> Sampling rate should be high for measurement of fast changing events

① Coil

> Simplest form of magnetometer

> Measures a fluctuating magnetic field

② Fluxgate Magnetometer

> Two coils around a core, one with AC

> High dynamic range

> Cassini: ① Fluxgate
② Ionized gas

> Galileo: 2 sets on a boom, use of spin to remove artificial field

> JUICE: fluxgates and scalar

Rocky Bodies

> For most bodies, magnetic axis is roughly aligned with rotation axis, but not all

> Bodies do not have a permanent magnet with sufficient strength, because of decay, temperature, and known composition

↳ In Earth, Curie temperature is reached below 100 km, and thus only the outer shell can have permanent magnetism

↳ Besides, ferromagnetic materials are not abundant enough, and magnetic fields gradually dissipate away

↳ For a dynamo to work, the current would have to pass through the entire core

↳ Convection is too slow to explain the field

↳ Also magnetic reversals found in ocean floors need to be explained

↳ Due to rotation (coriolis), aligns loops of electric current, which create the magnetic field [convective flows]

↳ Causes the coupling between rotation/magnetic axes

> In terrestrial planets, there is enough iron for the dynamo
> Jupiter and Saturn have metallic hydrogen and He
> Uranus and Neptune have other molecules (H_2O, CH_4, NH_3, H_2S)

> Mercury's low field is likely due to slow rotation

> Mars is not a dipole: field is remnant in crust no moving liquid inside

Sun and Solar Wind

> Corona: outermost part of solar atmosphere

↳ Heating and structure due to magnetic fields

> Solar magnetic field mainly from movement in radiation zone

> The termination shock is the region where solar wind is slowed down below $M=1$

> Heliopause: merging of solar wind with interstellar wind

> Solar wind travels in a spiral, consists of protons and electrons

> Space weather: ① UV radiation and X-rays
② CME particles
③ Cosmic-ray like particles

↳ Can disturb comms and electronics

↳ Particles are deflected due to Earth's magnetic field → magnetosphere

↳ Some enter near the poles, and get trapped → radiation belts, expl. by Lorentz force

Induced Magnetic Fields

> Bodies with a magnetic field will have a location where the solar wind pressure equals the magnetic field pressure, and bow shocks are created

↳ A body with an ionosphere has a similar interaction, where currents are set up, which inhibit the magnetic field from diffusing through the body

↳ When a non-conducting body is hit, the particles are absorbed, and the magnetic field is barely affected

↳ Conducting bodies generate an induced magnetic field due to the motion of the particles inducing a current, deflecting the magnetic field around the body

> Jupiter has a very large magnetosphere, and generates a co-rotating plasma disk due to the Lorentz force

↳ Io is hit from the back with the magnetic field lines, allowing transport from Io to Jupiter, creating auroras

> Jupiter induces a magnetic field in Europa, which is proof for a subsurface ocean

↳ Galileo measured a too fast changing magnetic field, indicating either a magnetic field, ionosphere, or induced magnetic field of Europa

↳ The first 2 were ruled out, and the last would be explained by a subsurface fluid layer

> The magnetic dipole potential

↳ $V = \frac{M \cdot r}{r^3}$

↳ $B = -\nabla V$

LECTURE 15: EXOPLANETARY SYSTEMS

> An exoplanet has negligible fusion H in stars, D in brown dwarfs

↳ Planetary mass $\lesssim 0.012\ M_\odot \approx 12\ M_J$

↳ Orbit around a star

> Stars are classified using their spectral characteristics Sun: G

> Parallax motion: nearby stars appear at different positions with respect to distant stars as the Earth moves along its orbit

↳ Parsec is defined as the distance for parallax angle 1"

↳ At 1 Pc, an angular separation of 1" corresponds to 1 AU, which is why we use it over e.g. lightyears

Detection Methods

① Direct Imaging

> Detect light emitted/reflected to create an image

↳ After detection, confirmation that it is a planet is needed

↳ Planets are extremely faint close to a bright source

↳ Brightness contrast is an issue

↳ Optimal for hot planets and long wavelengths

> Coronagraphs can be used to block the incoming bright light

> The star and planet need to be able to be resolved separately, giving a limit to the resolution diffraction

↳ Atmospheres distort wavefronts, making conditions worse

↳ Can be corrected by adaptive optics

> To prove it is a planet, the motion is observed to assess it is in orbit of a star, and to see it is not massive the cooling track is used to link luminosity and age to mass

② Radial Velocity

> First indirect method, looking at the star (no photons from the planet)

> Orbital motion of star-planet system CoM is used, from which a doppler shift is seen

↳ From Kepler's 3rd law, and $M_p << M_*$:

↳ $$\left(\frac{P}{365.25\,d}\right)^2 = \left(\frac{a}{AU}\right)^3 \left(\frac{M_*}{M_\odot}\right)^{-1}$$

> The stellar radial velocity is measured from the doppler shift

↳ $$\lambda_D - \lambda_0 = \lambda_0 \frac{\Delta V}{c}$$

↳ From that, and Kepler, the semi-major axis can be determined

↳ $$K = \frac{M_p}{M_p + M_*}\left(\frac{2\pi G(M_p + M_*)}{P}\right)^{1/3} \approx \frac{M_p}{M_*}\left(\frac{2\pi G M_*}{P}\right)^{1/3}$$

↳ However, this is for inclination 0° (sin factor added, 90° = edge-on)

↳ Minimum mass is measured

↳ Eccentric orbits require numerical fitting

↳ Multiple planets require hierarchy or numerical fit

③ Astrometry

> Measuring the reflex motion of the star in the plane of the sky

↳ Determine the motion around the CoM

↳ Precision from ground not good enough

↳ Gives true mass

LECTURE 16: EXOPLANETARY INSTRUMENTS & EXOMOONS

④ Transits

> Star flux decreases when planet crosses in front   edge-on system

↳ $\cos i < \frac{R_* + R_p}{a}$

↳ Since all i equally likely, transit probability is:

↳ $P_{trans} = \frac{R_* + R_p}{a}$

> Transit can be used to find period, resulting in semi-major axis, giving planet radius

↳ From radius and average density, a mass estimate can be made   from RV

> Periodic dimming can also be: ① Star spots (intrinsic variability)
② Grazing eclipsing binary
③ Eclipsing binary in background

↳ Need RV follow-up to confirm, also resulting in actual mass $\sin i \approx 1$

> Gravitational interactions between planets leads to variation in transit time

↳ Can be used to detect non-transiting planets or to constrain masses

⑤ Microlensing

> Based on gravitational lensing

↳ Conserves surface brightness: magnification results in a brighter object as more light is bent towards you

> Microlensing: detect lensing event by monitoring the brightness of source stars

> A point mass lens (star) has a point called a caustic where the mapping becomes a singularity if the bg source lies exactly behind it

↳ Results in the Einstein ring

↳ If the lens has a planet, properties change, but this is negligible except for a source in the caustic

↳ Star + planet has caustic curves, and if the source passes, it gets amplified infinitely, and planets can be detected

> Finds mass and separation

The Exoplanet Zoo

① Super-Jupiters

② Hot Jupiters
③ Super-Earths
④ Long period gas giants

> We have mostly found short period planets as these are easier to detect

↳ Planets are more common further out

> Much data, go over slides honestly

Life Outside the Solar System

> We need to look for biomarkers such as green, chlorophyll, ...

↳ Feature types: ① Surface
② Atmospheric — O_2 presence, although can be from photolysis of water

LECTURE 17: PLANET & SOLAR SYSTEM FORMATION

Star Formation

1. Molecular Cloud
2. Prestellar core
3. Protostar
4. Protoplanetary disk
5. Planetary System

> Dark Clouds: ① $M \approx 2 M_\odot$
② Cold, opaque at λvisible
③ Dust blocking light
④ Pressure counteracts gravity

> Light passing through interstellar clouds is reddened because of Rayleigh scattering

↳ Happens at a few μm → particles are smaller than 1μm

↳ Measuring extinction gives dust mass, gas from molecular lines ratio ~0.01

> Collapse of the clouds form stars, mass falls into the "massive" center

↳ $a_c = v_\theta^2 / r = j^2 / r^3$ ↳ $j = r v_\theta$ ↳ $a_g = G M_* / r^2$

↳ The cloud has some initial angular momentum, vector perpendicular to rotation axis, parallel to it gravity wins over centrifugal → disk formation

↳ Rotation is sped up as r decreases (cons. angular mom.)

↳ Evidence disk: SS planets roughly orbit in the same plane

> Using spectral energy distribution, the dust configuration can be found

> Temperature determines the thickness of the disk

> As material falls into the star, there will be an accretion shock leading to UV excess emission, which can be measured

> For all planets in SS, spread mass into an annulus, each having a surface density, which results in $\Sigma_{MMSN, gas}$ by fitting min mass solar nebula

From Dust to Pebbles

> To find out what happens to dust grains in gas in microgravity, we need experiments

① Drop tower
② simulations

↳ We can then map the parameter space

> Collisions between dust particles are very rare, between gas and dust common

↳ There is friction between the gas and dust

↳ $a_{drag} = -\frac{V_{dust} - V_{gas}}{\tau_s}$ τ_s stopping time; small grain → small τ_s, large grain → large τ_s

↳ τ_s proportional to surface to mass ratio, for spherical particles to radius

↳ For a particle in dust, the EoM is

↳ $\frac{d^2z}{dt^2} + \Omega^2 z + \frac{1}{\tau_s}\frac{dz}{dt} = 0$ Ω local angular velocity

↳ $\frac{d^2z}{dT^2} + z + \frac{1}{St}\frac{dz}{dt} = 0$ $St = \Omega\tau_s$, stokes number; $St \ll 1$: dust follows gas, $St \approx 1$: marginal coupling, $St \gg 1$: almost ballistic

↳ Settling velocity is size dependent

> For a large particle in a sea of smaller particles, it will sweep everything in a cylinder with radius R

> Idk what this all means, read back

Pebbles to Planetesimals

> With collisions, other things than sticking can happen bouncing, fragmentation, ...

↳ Depends on: ① Composition
② Local conditions
③ Charged particles
⋮

> For dust, settling near midplane as it moves towards highest gas pressure and gas is in hydrostatic equilibrium

↳ Dust has no pressure support: radial drift can happen

↳ $V_{drift} \sim \frac{-St}{1+St^2}\left(\frac{H}{r}\right)^2 V_\theta$ max for $|St| = 1$ → 1m boulder

↳ $\tau_{drift} = \frac{r}{|V_{drift}|}$

> Growing into pebbles is hard because they fall into the star

↳ Beat by: ① Grow faster than drift time scale unstable flow → concentrations
② Grow in places without drift radially structured disks

↳ Planetesimals are safe from drift

Planetesimals to Planets

> 2 bodies are approaching each other with impact parameter b

↳ Far away, gravity has no real impact yet

↳ $j_1 = r v_\theta = r \frac{\Delta V}{2} \sin\theta = \frac{b \Delta V}{2} = j_2$

↳ At closest approach, bodies pass each other with an unknown relative velocity

↳ $j = R_c V_{rel} / 2$

↳ Conservation of angular momentum:

↳ $R_c V_{rel} = b \Delta V$

> Initial energy:

↳ $E = m \Delta V^2 / 4$

↳ Closest approach:

↳ $E = m V_{rel}^2 / 4 - G m^2 / R_c$

↳ Conservation of energy:

↳ $\Delta V^2 / 4 = V_{rel}^2 / 4 - G m / R_c$

↳ Combining:

↳ $b^2 = R_c^2 + \frac{2 G m R_c}{\Delta V^2}$

↳ Collision:

↳ $R_c < 2 R_p$

or

↳ $b^2 < 4 R_p^2 + \frac{8 G m R_p}{\Delta v^2} = 4 R_p^2 \left(1 + \frac{v_{esc}^2}{\Delta v^2}\right)$ $v_{esc} = \sqrt{2 G m / R_p}$

↳ Let:

↳ Gravitational focusing factor $\sqrt{1 + \frac{v_{esc}^2}{\Delta v^2}}$

↳ Effective size $R_{eff} = R_p \sqrt{1 + v_{esc}^2 / \Delta v^2}$

↳ More massive bodies have more collisions as $v_{esc}^2 \propto m$

↳ If $\Delta v \neq f(m)$, runaway growth

↳ $\frac{dm}{dt} = \rho_{swarm} \Delta v \, \pi R_{eff}^2 \sim m^{4/3}$

↳ However, planetesimals start to spin, resulting in oligarchic growth, and the mass reservoir is finite, making growth stop when everything in the 'feeding zone' has been accreted

↳ Feeding zone: annulus of width $2 R_H$

↳ $R_H = a \left(\frac{m}{3 M_*}\right)^{1/3}$ Hill radius

↳ limit feeding zone mass is the isolation mass

↳ $\frac{M_{iso}}{M_*} = \left(\frac{4\pi \Sigma_p a^2}{3^{1/3} M_*}\right)^{3/2}$

↳ After depletion of feeding zones, giant impacts happen → terrestrial + Moons

→ For gas giants: ① Core accretion model
② Gravitational instability model

↳ ① Requires high core mass and low temperature

↳ Takes long

↳ ② Make a disk massive and cold enough that it collapses

↳ Possible at larger distances