Overview of the Solar System

Patterns in Orbits
- Planetary orbits are almost coplanar
    - Mercury's orbit deviates most
- Planet's orbital planes are the same as Sun's equatorial plane
    - The orbital planes of satellites are near equatorial planes of their planets
- Rotational axes are mostly perpendicular to orbital planes (Except Uranus)
- Orbital and rotation directions are the same for planets and most satellites - except Venus

Patterns in Physical Properties
- Inner Solar System contains mainly bodies with high amounts of metals, rocks, etc
- Outer Solar System contains lighter elements like gas or ice
- Satellites usually have the same chemistry of their planet

Terrestrial vs Jovian (Giant) Planets
- Terrestrial Planets
    - In the inner part of Solar System
    - Small
    - Rocky (High density)
    - Few moons, no rings
- Giant Planets
    - Outer part of Solar System
    - Large
    - Gaseous (Low density)
    - Many moons
    - Rings
    - Rotate rapidly

Earth as a Prototype of Terrestrial Planets
- Differentiated interior
- Strong magnetic field
- Active surface
    - Volcanoes
    - Continental plates
    - Liquid water
- Atmosphere
    - Nitrogen, oxygen, minor amounts of other gases
    - Greenhouse effect

Earth's Interior is Differentiated
- Rocky Crust (Low density)
- Mantle (Med density)
- Metal core (highest density)
- Rigid lithosphere (crust and part of mantle)

Properties of Earth's Interior

- Radial structure - Inner core, outer core, mantle, crust

How are Planet Interiors Heated?

- Produced by **Accretion, Differentiation, Radioactive Decay**
    - Accretion - Things hitting the planet, gravitational potential energy converted to kinetic energy, then thermal energy
    - Differentiation - Light materials rise to surface, dense materials fall to core - converts gravitational potential energy to thermal energy
    - Radioactive Decay - Mass-energy contained in nuclei is converted to thermal energy
    - Proportional to planet's mass

How are Planets cooled?

- By **convection, conduction, radiation**
    - Convection - Hot rock rises and cooler rock falls in a mantle convection cell
    - Conduction - After convection brings heat to base of lithosphere, conduction carries heat through rigid lithosphere to surface
    - Radiation - At surface, energy is radiated into space

Heating vs Cooling

- Cooling proportional to surface area (r^2)
- Heating proportional to mass (r^3)
- Therefore, larger bodies will cool slower

Planetary Magnetic Fields

- Rotating metallic core will act as a dynamo, produce magnetic field
- Earth's magnetic field comes from the motion of charged particles in outer liquid core

Continental Drift

- Subduction and sea floor spreading is due to plate motion
- Plates are driven by convection in upper mantle

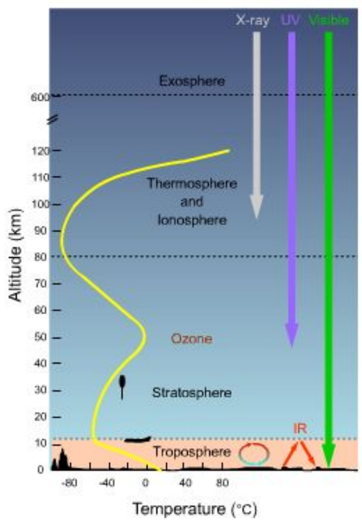
Earthquakes occur mostly at plate boundaries

Planetary Atmospheres

- Vertical structure - pressure and temp changes with altitude
- Greenhouse effect caused by surface heating and clouds
- Earth's atmosphere was produced by outgassing, original mostly lost
- Surface temp is a combination of solar heating, IR radiation trapped by cloud layer and a hot interior
- Earth's atmosphere blocks some wavelengths, transmits others
    - Sunlight received by one hemisphere is emitted in all directions
- Structure of Earth's atmosphere
    - Exosphere
        - Heated by Solar UV and Xray
        - Region of greatest escape (high temperature and altitude)
    - Thermosphere and Ionosphere
        - Xrays heat and ionize
    - Stratosphere

- Heated by UV light
- No convection

- Troposphere
  - Topped by clouds
  - Traps IR from surface
  - Radiation and convection are important



Heat Trapping

- Atmospheric structure depends on temperature, solar radiation
- Cloud layers are the main factor in trapping heat
  - Also CO_2

Greenhouse Effect

- Earth's atmosphere transparent to visible light - heats surface
- Surface cools by emitting IR
- Earth's atmosphere not transparent to IR
  - CO_2 absorbs the IR wavelengths
- Atmosphere heats up to balance the heat from sunlight
- Increasing CO_2 amount will increase the temperature

Atmospheres lose mass by thermal escape, solar winds, impacts, condensation and chemical reactions

Escape Velocity

- Gas temp correlates with its particle's velocities
  - Probability of escape is related to the peak thermal velocity
- Early Solar System hotter than today - thus it contributed to a loss of atmosphere
- Atmospheric gases escape if they have low mass (Hydrogen, helium)

To retain a gas of mass m (amu) on a planet with mass M and radius R (in Earth units) the temperature, $T < 75K\left(\frac{mM}{R}\right)$

How atmospheres gain mass

- Atmospheres gain gas due to:
  - Outgassing
  - Evaporation
  - Impacts

Effect of heating on circulation patterns

- Circulation cells in each hemisphere
- Warm air rises near equator, when it reaches poles it has cooled, and warms as it moves to equator
- Rotation of the Earth has an effect on circulation - air goes in circular patterns

Coriolis Effect

- Causes circulation cells to divide
- Three cells per hemisphere on Earth - varies per planet

Properties of terrestrial planets

Object	r	m	Density	Atmosphere	Magnetic Field	Moons
Mercury	0.382	0.055	0.984	No	Weak	No
Venus	0.949	0.815	0.951	Yes	No	No
Earth	1.0	1.0	1.0	Yes	Yes	1
Moon	0.272	0.012	0.605	No	No	No
Mars	0.533	0.107	0.711	Yes	Weak?	2

- Mercury
  - Heavily cratered, large impact feature (Caloris Basin)
  - Solid interior
  - Weak magnetic field (Mystery)
  - Evidence of lava flow
  - Long cliffs are indications of cooling and shrinking of care + mantle
- Venus
  - Has a dense, hot atmosphere, majority CO_2
    - Sulphuric acid clouds and extreme greenhouse effect
    - Atmospheric pressure is 90 times more than Earth
    - No magnetic field - possibly b/c of slow rotation
  - Few craters - evidence of possible planet-wide resurfacing
  - Has some continents, maybe volcanos
  - Interior not well known
  - Rotation period is 243 days retrograde
    - Synodic orbital period = rotation period = ⅔ Earth year
  - Venus's Atmosphere
    - Has denser clouds, blocks more IR
    - Greenhouse effect greater on Venus than Earth
    - Not much sunlight gets to Venus

- <u>Mars</u>
    - Two moons - Phobos and Deimos
    - Thin atmosphere, majority CO_2
    - Surface pressure only 0.01 times that of Earth
        - Thin air
    - Temp is 220K
    - Very weak magnetic field
    - Surface features
        - Red b/c of iron oxides
        - Long canyons
        - Many volcanoes (Largest in Solar System - Olympus Mons)
        - Polar caps have frozen CO_2, indicates season “exchange” with the atmosphere
        - Rotation of 24 hrs
- <u>Moon</u>
    - 1/83 times the mass of Earth
    - Moon has the largest moon-planet ratio in the Solar System
    - No atmosphere
    - Side away from Earth is heavily cratered
    - Tidally “Locked” to Earth - we only see the same side of the Moon
    - Moon’s surface has
        - Maria - Smooth, dark areas
        - Highlands - Cratered, bright areas
        - Maria areas younger than Highland (Confirmed through samples)
    - Interior is differentiated, but not as bad as Earth’s

<u>Giant (Jovian) Planets</u>

- Large size
- Low density
- Fast rotation (More extreme weather)

	Planet	r	m	Density	P_{rot}	Axis tilt	Magnetic Field	$g_{surface}$
		(km)	(kg)	(kg/m^3)	(d)	(°)		(m/s^2)
	Earth	6,378	5.97×10^{24}	5,520	0.9973	23.45	Yes	9.8
Relative to the Earth	Earth	1.0	1.0	1.0	1.0	0.0	Yes	1.0
	Jupiter	11.2	317.9	0.24	0.41	3.08	Yes	2.36
	Saturn	9.5	95.2	0.12	0.44	26.73	Yes	0.92
	Uranus	4.0	14.5	0.23	-0.72	97.92	Yes	0.91
	Neptune	3.8	17.1	0.30	0.67	29.6	Yes	1.14

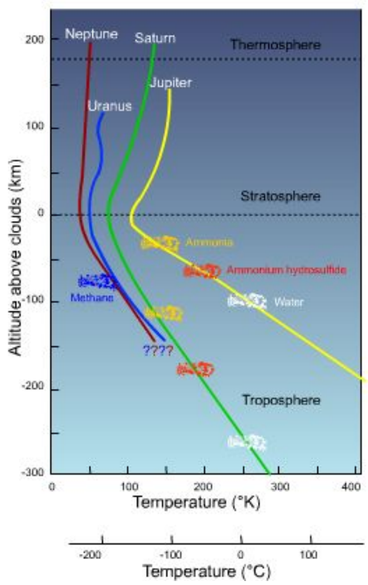
- They are like rapidly rotating “gravitationally bound” balls of fluid
- Gravity tends to pull fluid into a sphere, but the rotation flattens it into an “ellipsoid”

<u>Jupiter</u>

- Interior is differentiated (Actually all Jovian planets)

- Mantle is mostly metallic hydrogen
- Core is mostly rocky and metallic hydrogen compounds

Jovian Atmospheres

- Similar to terrestrial atmosphere w/ temp changes with altitude
    - Different cloud layers
- They have similar atmospheres to each other but are different in their max temperature, pressure and some composition
    - 

- Neptune and Uranus' blue colour is caused by methane
    - Absorbs red wavelengths, reflects blue wavelengths

Jovian Magnetic Fields

- Have strong magnetic fields and large magnetospheres
- Uranus and Neptune's magnetic fields are tilted away from their rotation axes

Internal Heat

- Three out of four Jovian planets have internal heat sources
    - Jupiter, Saturn, Neptune - but the source is unknown

Summary of Jupiter

- Layered atmosphere
    - Hydrogen/helium/methane/ammonia/water
    - Strong banding from cloud layers
    - Strong magnetic field
    - No true surface
    - Oblate planet - fast rotation
    - Hotter than expected - not Greenhouse, planet is contracting?

Summary of Saturn

- Similar to Jupiter, but is smaller
- Rings are the most massive + prominent

Summary of Uranus

- Accidentally discovered telescopically in 1781

- Faint features with blue atmosphere
- Atmosphere of hydrogen, helium, methane but no ammonia
- Strong magnetic field
- Hydrogen core
- Rotation axis is tilted 98 degrees, causes extreme seasons

<u>Summary of Neptune</u>
- Position was predicted from observing Uranus
- Discovered in 1846
- Like Uranus, more methane
- More cloud features
- Warmer than Uranus

<u>Moons around Giant Planets</u>
- Jupiter
    - Io
        - Geologically active (Volcanos)
            - Most volcanically active
        - Covered in orange sulphur compounds
        - Tied to Jupiter's magnetic field
        - Eccentric orbit means that there is a continuous tidal force change
            - Causes Io's interior to flex, causes tidal heating
    - Europa
        - Water ice on surface, is possibly over liquid water
        - Smooth surface with few craters
    - Ganymede
        - Largest moon in solar system
        - Water ice over much of surface
        - Has similarities to Mars

    - Callisto (Oldest surface)
        - Heavily cratered
        - Concentric circular ridges are signs of large impacts
    - Io, Europa, Ganymede have orbital resonance - 4:2:1 orbits respectively

- <u>Saturn's Moons</u>
    - Has many moons, some may not be discovered yet
    - Titan is largest - contains methane and nitrogen
    - Other moons: Mimas, Enceladus, Tethys, Dione, Rhea, Iapetus
- <u>Uranus' Moons</u>
    - More than 20 small moons
    - Five midsized moons - Miranda, Ariel, Umbriel, Titania, Oberon
    - Miranda has a very fractured surface
- <u>Neptune's Moons</u>
    - Five small inner moons near ring system

        - Two larger icy moons
        - Five small outer retrograde moons
        - Triton is largest
            - Much larger, thin nitrogen atmosphere
            - retrograde
            - spiraling in towards Neptune
- Saturn's Rings
    - Rings occur within "Roche Limit" of Saturn, where rocks (moons) break up because of tidal effects
    - Three major rings, A,B,C with gaps b/w them
        - "Cassini's Division"
        - Composed of icy particles b/w 1 micron and 10 meters
    - Voyager discovered several other rings
        - Rings within rings - like record grooves - called "spiral density waves"
        - Short lived spokes
            - Possibly caused by charged particles briefly suspended above the plane
        - Braided rings
        - "Shepherd" satellites
            - They control the width of the rings and make gaps
                - Tidal effect of the moons
        - Rings are very thin - tens of meters
- Jupiter's Rings
    - Quite small - possibly debris
- Uranus' Rings
    - IR images shows rings around Uranus and some of moons
- Neptune's Rings
    - Narrow and bright with dusty regions + large gaps

Small Bodies and Scaling Astronomical Equations

- The inner Solar System is filled with asteroids and other small bodies

Scaling Astronomical Equations

- Astronomers often write equations in a form that shows "default" value of the result with a scaling to show the variation as "inputs" change
-

Surface temperature of a planet $T\left({}^{\circ}\mathrm{K}\right)^4 = \boxed{6.00 \times 10^9}\left(1 - A\right)\left(\frac{L}{L_\odot}\right)\frac{1}{D\left(\mathrm{AU}\right)^2}$

Vis-viva equation $v\left(\mathrm{km/s^2}\right)^2 = \boxed{883}\left(\frac{M}{M_\odot}\right)\left(\frac{2}{r\left(\mathrm{AU}\right)} - \frac{1}{a\left(\mathrm{AU}\right)}\right)$

Gravitationally unstable mass $M_{Jeans}\left(M_\odot\right) = \boxed{2}\left(\frac{c}{0.2\,\mathrm{km/s}}\right)^3\left(\frac{n}{10^3\,\mathrm{cm}^{-3}}\right)^{-\frac{1}{2}}$

<u>Pluto</u>

- Very eccentric orbit
- For 20 of its 248 orbit it’s closer to the Sun than Neptune
- It’s moon is Charon
    - Their distance allows us to measure the mass of Pluto w/ Kepler’s third law
    - Eclipses let us measure diameters of both of them
- It’s atmosphere has a small amount of nitrogen that will probably freeze out in the next 100 yrs
- Pluto’s density is larger than expected
    - Charon is less dense
    - possibly b/c Charon was formed from a large impact at Pluto

Dwarf Planet - In orbit around Sun, massive enough to be spherical, hasn’t cleared out it’s surrounding area, lots of stuff around it

- Prominent examples
    - Pluto, Eric, Ceres