Meteorites

Types

There have been about 1050 observed falls and about 31,000 finds.

- Stony meteorites
  - Chondrites (85.7% of falls, 52% of finds) oldest, 4.55 Byrs old.
    - Ordinary contain both volatile and oxidized elements, formed in inner belt, and are the most common type.
    - Carbonaceous contain more volatiles, formed in outer belt.
    - Enstatite contain more refractory elements, formed in the inner SS.
  - Achondrites (7.1% of falls, 1% of finds) show evidence of igneous processes.
    - HED group
    - SNC group (Martian)
    - Aubrites
    - Urelites
    - Eucrites (Vesta)

- Stony iron (1.5% of falls, 5% of finds)
  - Pallasites
  - Mesosiderites

- Iron (5.7% of falls, 42% of finds) formed in meteorite parent body cores.
Meteorites are

- **primitive**: unaltered (mostly chondrites, esp. carbonaceous chondrites)
- **differentiated**: evolved, products of melting, separation

Interesting discoveries:

- Organic compounds in carbonaceous chondrites (Allende, Murchison) are equally left- and right-handed
- Isotopic anomalies in carbonaceous chondrites: $^{16,17,18}$O, $^{26}$Mg (from $^{26}$Al, half-life 720,000 yrs)
- SNC meteorites traced to Mars
- Possible microfossils, complex hydrocarbons, biominerals in SNC meteorite ALH 84001
- Eucrites traced to Vesta
- Sayh al Uhaymir 169 is a meteorite from the Moon
- The meteorite Kaiduri is possibly from Mars’ moon Phobos

- On September 15 2007 a chondritic meteorite hit near Carancas, Peru and poisoned about 30 villagers that approached the impact site (600 more had provoked psychosomatic ailments). The impact caused boiling of arsenic-contaminated ground water from natural deposits. The local province is turning this into a tourist attraction.
Rita B. Lattimer, AST 248, Lecture 18 – p.3/24

\section*{Tidal Forces}

\begin{align*}
F_t &= \frac{GMm}{(R - r)^2} - \frac{GMm}{(R + r)^2} \\
&= GMm\left[\frac{(R + r)^2 - (R - r)^2}{(R - r)^2(R + r)^2}\right] \\
&\approx GMm\frac{4Rr}{R^4} = GMm\frac{4r}{R^3}.
\end{align*}

Tides generate a tidal bulge along the equator. As the object rotates, the bulge is dragged around the object opposite to the spin. The pushing and pulling of the planetary material generates frictional heat and produces a torque (a force that changes angular momentum). The strong tides have synchronized, or tidally locked, the rotation of the Moon with its orbital period, 28 Earth days. Tides are pushing the Moon away.
Effects of Tidal Forces

- Tides or tidal bulges: changing sea levels
- Resonances: rotations and orbits of bodies become synchronized in integer ratios
  - Mercury in a 3:2 rotation:orbit resonance
  - Moon locked to Earth; a 1:1 rotation:orbit resonance
  - Venus and Earth in a 13:8 orbital resonance
  - Phobos & Deimos locked to Mars
  - Io, Europa, Ganymede, Callisto and 4 others locked to Jupiter
  - Mimam, Enceladus, Tethys, Dione, Rhea, Titan, Iapetus and 8 others locked to Saturn
  - Miranda, Ariel, Umbriel and Titania locked to Uranus
  - Proteus and Titania locked to Neptune
  - Charon and Pluto locked to each other; Nix & Hydra in 1:4 and 1:6 resonances
  - Pluto and many Kuiper Belt Objects in a 3:2 orbital resonance with Neptune
  - Tau Bootis locked to an orbiting giant planet
  - Gliese 581 b and c are locked to parent star Gliese 581
- Tidal heating: Satellites rotate at a constant speed, but in an eccentric orbit the orbital speed varies with separation (Kepler's 2nd Law). The tidal bulge is pulled back and forth; the friction heats the interior.
  - An extreme case is the Io, Europa and Ganymede system in a 4:2:1 orbital resonance that makes Io tremendously volcanically active and maintains a liquid shell under Europa’s icy crust.
• Roche limit: Minimum distance from a planet that a solid satellite can orbit without tides pulling it asunder.  
Equate tidal force and self-gravity of 2 moonlets of mass $m$ and radius $r$:

$$GMm \frac{4r}{R^3_R} = G \frac{m^2}{4r^2}, \quad \text{or} \quad R_R = 2^{4/3} r \left( \frac{M}{m} \right)^{1/3}.$$  

Planet’s average density is $\rho_\oplus = 3M_\oplus / (4\pi R^3_\oplus)$  
moon’s average density is $\rho_m = 3m / (4\pi r^3)$  

Implies that the Roche limit is

$$R_R = 2^{4/3} \left( \frac{\rho_\oplus}{\rho_m} \right)^{1/3} R_\oplus \approx 2.5 - 3R_\oplus.$$  

• Rings and satellites: Large satellites must orbit outside the Roche Limit. Rings can extend to the Roche Limit.  
  • All the Jovian planets have rings; Outer edge of Saturn’s A ring is at $2.3R_\text{J}$  
• Eventual loss of prograde satellites: Frictional loss of angular momentum leads to expanding orbits.  
• Destruction of retrograde satellites: Retrograde satellites have shrinking or decaying orbits and will eventually fall within the Roche Limit and be destroyed.  
  • Triton will be destroyed in 100 Myr to 1 Gyr.
The Moon

- The moon is in synchronous rotation
- Only 1 side of moon visible from Earth
- Bright regions are heavily cratered highlands
- Dark regions, called mare, are lava-flooded lowlands
- Near side of moon is 31% mare; far side is 2% mare
- Craters due to impact; largest is the South-Pole Aitken basin on the far side, 2240 km diameter and 13 km deep – the largest crater in solar system
- The moon is surface, called the regiolith, is composed of broken rocks and dust
**Lunar Interior**

Seismometry determines lunar structure:

- **Crust**—50 km thick solid magma ocean
- **Mantle**—to depths of about 800 km
- **Core**—small, semi-liquid or plastic (as indicated by moon’s time-variable rotation)
Lunar Surface Composition

- No sedimentary rocks (limestone, shale) on the Moon
- All lunar rocks are igneous (cooling lava)
- Nearly complete lack of water in lunar rocks, with the exception of a small amount of water hidden in deep craters at lunar north and south poles (discovered by Clementine and Lunar Prospector)
- General lack of volatile elements (Hg, Na, K, ... ) in lunar rocks
- General lack of iron and iron-loving (siderophile) elements (Ni, Mn, ... ) in lunar rocks.
**Theories of Moon’s Origin**

Must explain lack of iron and lack of volatiles and similarities of other chemical and isotopic properties; also the large angular momentum of Earth-moon system.

- *Daughter*, or fission. Needs too much spin, cannot explain lack of volatiles. Also predicts moon should orbit in equatorial plane of Earth.

- *Sister*, or co-accretion. Cannot explain lack of iron.

- *Capture* theory. Difficult to make regular orbit, cannot explain isotopic similarity to Earth. Statistically improbable.

- *Collision* of a Mars-sized object (called Theia) with early Earth. Explains lack of volatiles and iron, preserves other similarities. Thought to occur 30-50 million years after Earth’s formation.

http://starchild.gsfc.nasa.gov/docs/StarChild/questions/question38.html
**Lunar Chronology**

- Moon formed 4.4–4.5 Byrs ago, by impact of minor planet with Earth (?)
- Original rocks obliterated by extreme meteoroid bombardment; oldest surviving rocks date to 4.3 Byrs.
- Highland regions are oldest and provide evidence of extensive meteoroid bombardment until 3.9 Byrs ago.
- Radioactive heating melted interior of Moon, semi-liquid regions reaching depths of 200 km 3–3.5 Byrs ago.
- Last large impacts fractured crust, producing massive lava flows from interior which filled large impact basins 3–3.5 Byrs ago. This created the *lunar mare*.
- Moon has been geologically quiet since 3.1 Byrs ago, with the exception of alterations caused by occasional meteoroid impacts, solar wind, cosmic rays and human spacecraft. The portion of the interior that is semi-liquid is shrinking and is almost gone now.
Mercury

- The innermost and smallest planet.
- Rotation rate is slow: 59 Earth days, exactly 2/3 of the Mercury year (the orbital period about the Sun), 88 days.
- Heavily cratered surface
- Surface similar to moon's with extensive mare regions and heavy cratering.
- Cratering indicates extremely old surface and long-time geologic inactivity.
- Temperatures on Mercury are extreme; 90 K at night to 700 K by day (but still not quite as hot as Venus!).
- Tides have forced Mercury's pole perpendicular to orbital plane; polar crater bottoms are permanently in shade with temperatures near 150 K allowing survival of ice.
• Largest impact basin is the Caloris Basin 1300 km in diameter (top). At the antipode of this basin is “weird terrain” (bottom) thought to be due to shock convergence.

• Mercury’s density is large, its uncompressed density is 20% larger than Earth’s, indicating massive iron content (up to 70%).

• Molten iron core has radius 3/4 of planet; mantle about 20%; crust about 5%.

• Large iron content indicates catastrophic, collisional origin for Mercury. Over half its mass was lost.
Mercury’s Rotation

- Rotation rate deduced using radar from Earth. Rotation causes a Doppler shift in radar’s frequency.
- Rotation is tidally locked, indicative of a strong tidal resonance due to Sun.
- The “solar” day is 2 Mercury years long, causing strange seasons.
- The 3:2 resonance is a consequence of the fact that at perihelion, the rotational surface velocity at the point nearest the Sun almost cancels the orbital velocity. At noon at perihelion, the Sun appears to hang nearly motionless overhead.
Venus

- Venus’ mass and radius are nearly the same as Earth.
- Rotation rate is slow and retrograde: 243 Earth days, longer than its year (225 Earth days). Perhaps caused by solar tides, atmospheric friction or collisional impact. Has a 13:8 orbital resonance with Earth, known to Babylonians in 1900 BC and the Maya, and a 13:5 resonance between its synodic and orbital periods.
- Atmosphere is thick (90 times \( \oplus \), equal to 900 m below sea level) and hot (750 \( K \)).
- Highly reflective clouds nearly cancels Venus’ proximitiy to Sun, so Venus absorbs only 5% more solar energy than the Earth.
- High temperature caused by Greenhouse effect, raising temperature by 470 \( K \) (45 \( K \) on the Earth, and 5 \( K \) on Mars, for comparison).
- Surface obscured by sulfuric acid clouds high in Venus’ atmosphere.
- Near surface, atmosphere is clear, but density of atmosphere causes peculiar bending of light so that it looks like the bottom of a fishbowl.
- Surface explored by radar from Earth and satellites in orbit around Venus. Surface is solid, no lakes, and few mountains. Craters and volcanos exist, but little evidence of plate tectonics, due to absence of water in planet’s crust.
- Lack of tectonics supported by low \( \text{Ar}^{40} \) (from decay of \( \text{K}^{40} \)) in atmosphere.
- Evidence for “snow” made of tellurium or lead sulfide on mountain tops
- Water is now completely lacking from Venus but was abundant in past, as deduced from high D/H ratio in atmosphere, 100 times Earth’s value.
- Venus evolved divergently from the Earth because it is too close to the Sun.
Atmosphere of Venus

Atmospheric composition: 96.5% CO₂, 3.5% N₂, 0.015% SO₂ (forms visible clouds with H₂SO₄), 0.007% Ar, 0.002% H₂O, 0.0017% CO, 0.0012% He, 0.0007% Ne
**Greenhouse Effect**

Important greenhouse gases: $\text{H}_2\text{O}$ (36%), clouds (25%), $\text{CO}_2$ (20%), $\text{O}_3$ (2%), $\text{CH}_4$ (1%), $\text{N}_2\text{O}$ (1.5%), fluorocarbons (0.5%)

Clathrate greenhouse: release of $\text{CH}_4$ from Siberian tundra could trigger large change

Runaway greenhouse effect on Venus:
Rising temperature boils oceans, increases $\text{H}_2\text{O}$ concentration in atmosphere. Higher temperatures then sublime $\text{CO}_2$ from rocks, putting more $\text{CO}_2$ in atmosphere.
Water Was Lost on Venus

Deuterium is heavy hydrogen and weighs twice as much as normal hydrogen. Velocity of gas molecules in atmosphere is proportional to the square root of their masses. Normal hydrogen atoms are thus preferentially lost from dissociated water molecules.

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Venus' early water was hot enough to remain in a gaseous form and high enough to be dissociated by ultraviolet light (very short wavelength) from the Sun. The low-mass hydrogen molecule resulting from the dissociation moved fast enough to escape Venus and the higher-mass (and slower moving) oxygen atom combined with other atoms. Eventually the water disappeared. The Earth created an ozone shield above the "cold trap" (height where the temperature is cold enough for water to freeze and fall back to the ground). The UV light cannot reach the water because the ozone absorbs the UV light. The ozone also shields life from the harmful UV light.

Radar Map of Venus
Magellan topographical map
• Successful spacecraft exploration included Mariner 2, 5 and 10; Venera 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16; Pioneer Venus Orbiter and Pioneer Venus Multiprobe; Vega 1 and 2; Magellan; Venus Express; Messenger.

• Planned exploration includes Planet-C (2010, Japan), BepiColombo (2013, ESA), Venus In-Situ Explorer (2013, NASA)
Impact crater

About 1000 craters known, none smaller than 3km because of atmosphere shield

Pristine condition of most volcanos indicates cyclic resurfacing from catastrophic subduction about 500 Myr ago

Pancake volcanos

$\text{SO}_2$ concentrations changed by 10 between 1978 and 1986, indicating active volcanism
Head et al., J. Geophys. Res. 97, 13153 (1992)
Volcanoes on Venus

- Venus has more volcanoes than any planet in the solar system, over 55,000 larger than 1 km, and possibly a million in total.
- Volcanoes form in fields, as a group, 100–200 km wide, which are former hot spots where magma rising from mantle broke through crust.
- No active volcanoes are known, but some may be active. Evidence for recent activity includes:
  - variations in SO\textsubscript{2} levels, a gas that is rapidly depleted from the atmosphere by photodissociation, have been seen by ESA’s Venus Express
  - two orbiters have detected radio bursts similar to lightning discharges which often occur in connection with volcanic activity.
- High atmospheric pressure, lack of winds and water, make volcanic features appear fresh.
- There is no obvious evidence for plate tectonics: linear volcanic chains, subduction zones or continents.
- Volcanic style is not eruptive, but involve fluid flows:
  - atmospheric pressure too high, requires very high gas content to erupt
  - lack of water, the usual gas driving lava explosions on the Earth
  - no subduction zones, where explosive volcanism is common on the Earth
Five inferior conjunctions of Venus repeat in a precessing pentagram

Positions shown on:
2007 Aug 18 20:21:04 UT

Venus motion shown
(1 day for 2915 days)

- Mars
- Venus
- Earth
- Sun