Comparative Planetology of the Terrestrial Planets

Chapter 17: A Travel Guide to the Terrestrial Planets

Core, Mantle, Crust, Atmosphere

All terrestrial planets have a similar structure of

- A liquid core
- A mantle of molten lava
- A crust of solid, low-density rocks
- An atmosphere (large range of compositions and pressures)

The Early History of Earth

Earth formed 4.6 billion years ago from the inner solar nebula.

Four main stages of evolution:

- Two sources of heat in Earth’s interior:
  - Potential energy of infalling material
  - Decay of radioactive material

Most traces of bombardment (impact craters) now destroyed by later geological activity.

Seismology

Direct exploration of Earth’s interior (e.g., drilling) is impossible.

Earth’s interior can be explored through seismology:

Earthquakes produce seismic waves.

Seismic waves do not travel through Earth in straight lines or at constant speed.

They are bent by or bounce off transitions between different materials or different densities or temperatures.

Such information can be analyzed to infer the structure of Earth’s interior.

The Active Earth

About 2/3 of Earth’s surface is covered by water.

Mountains are relatively rapidly eroded away by the forces of water.
**Tectonic Plates**

Earth's crust is composed of several distinct tectonic plates, which are in constant motion with respect to each other → Plate tectonics

Evidence for plate tectonics can be found on the ocean floor ... and in geologically active regions all around the Pacific

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**Plate Tectonics**

Tectonic plates move with respect to each other.

Where plates move toward each other, plates can be pushed upward and downward → formation of mountain ranges, some with volcanic activity, earthquakes

Where plates move away from each other, molten lava can rise up from below → volcanic activity

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**Active Zones Resulting from Plate Tectonics**

Volcanic hot spots due to molten lava rising up at plate boundaries or through holes in tectonic plates

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**Earth's Tectonic History**

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**History of Geological Activity**

Surface formations visible today have emerged only very recently compared to the age of Earth.

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**The Atmosphere**

Earth had a primeval atmosphere from remaining gases captured during formation of Earth

Atmospheric composition severely altered (→ secondary atmosphere) through a combination of two processes:

1) Outgassing: Release of gases bound in compounds in Earth’s interior through volcanic activity

2) Later bombardment with icy meteoroids and comets

Composition of Earth’s atmosphere is further influenced by

• Chemical reactions in the oceans,
• Energetic radiation from space (in particular, UV)
• Presence of life on Earth
Human Effects on Earth’s Atmosphere

The Greenhouse Effect

Earth’s surface is heated by the sun’s radiation. Heat energy is re-radiated from Earth’s surface as infrared radiation. CO₂, but also other gases in the atmosphere, absorb infrared light → Heat is trapped in the atmosphere. This is the greenhouse effect. The greenhouse effect occurs naturally and is essential to maintain a comfortable temperature on Earth, but human activity, in particular CO₂ emissions from cars and industrial plants, is drastically increasing the concentration of greenhouse gases.

The Moon: The View from Earth

From Earth, we always see the same side of the moon. The moon rotates around its axis in the same time that it takes to orbit around Earth:

- Tidal coupling: Earth’s gravitation has produced tidal bulges on the moon; tidal forces have slowed rotation down to same period as orbital period.

Lunar Surface Features

- Two dramatically different kinds of terrain:
  - Highlands: Mountainous terrain, scarred by craters
  - Lowlands: ~ 3 km lower than highlands; smooth surfaces:
    - Maria (pl. of mare): Basins flooded by lava flows

Impact Cratering

Impact craters on the moon can be seen easily even with small telescopes. Ejecta from the impact can be seen as bright rays originating from young craters.

Impact Cratering (II)

Some meteorites found on Earth have been identified chemically as fragments of the moon’s surface, ejected by crater impacts.

History of Impact Cratering

Rate of impacts due to interplanetary bombardment decreased rapidly after the formation of the solar system.

Most craters seen on the Moon’s (and Mercury’s) surface were formed within the first ~ 1/2 billion years.

Notice the exponential scale in this graph of the cratering rate. Only half a billion years after the origin of the solar system, the cratering rate had fallen by a factor of 10,000. Today, the rate is very low and no crater is known with certainty to have been formed on the moon in historic times.
Apollo Landing Sites
First Apollo missions landed on safe, smooth terrain. Later missions explored more varied terrains.

Moon Rocks
All moon rocks brought back to Earth are igneous (= solidified lava)
No sedimentary rocks => No sign of water ever present on the moon.
Different types of moon rocks:
- Vesicular (= containing holes from gas bubbles in the lava) basalts, typical of dark rocks found in maria
- Breccias (= fragments of different types of rock cemented together), also containing anorthosites (= bright, low-density rocks typical of highlands)
- Older rocks become pitted with small micrometeorite craters

The History of the Moon
Moon is small; low mass → rapidly cooling off; small escape velocity → no atmosphere → unprotected against meteorite impacts.
Moon must have formed in a molten state (“sea of lava”);
Heavy rocks sink to bottom; lighter rocks at the surface
No magnetic field → small core with little metallic iron.
Surface solidified ~ 4.6 – 4.1 billion years ago.
Heavy meteorite bombardment for the next ~ 1/2 billion years.

Origin of Mare Imbrium
Terrain opposite to Mare Imbrium is jumbled by seismic waves from the impact.

Formation of Maria
Impacts of heavy meteorites broke the crust and produced large basins that were flooded with lava

The Origin of Earth’s Moon
Early (unsuccessful) hypotheses:
- Fission hypothesis: Break-up of Earth during early period of fast rotation
  Problems: No evidence for fast rotation; moon’s orbit not in equatorial plane
- Condensation hypothesis: Condensation at time of formation of Earth
  Problem: Different chemical compositions of Earth and moon
- Capture hypothesis: Capture of moon that formed elsewhere in the solar system
  Problem: Requires succession of very unlikely events
Modern Theory of Formation of the Moon

The Large-Impact Hypothesis

• Impact heated material enough to melt it → consistent with “sea of magma”
• Collision not head-on → Large angular momentum of Earth-moon system
• Collision after differentiation of Earth’s interior → Different chemical compositions of Earth and moon

Mercury

Very similar to Earth’s moon in several ways:
• Small; no atmosphere
• Lowlands flooded by ancient lava flows
• Heavily cratered surfaces

Most of our knowledge based on measurements by Mariner 10 spacecraft (1974 - 1975)

Rotation and Revolution

Like Earth’s moon (tidally locked to revolution around Earth), Mercury’s rotation has been altered by the sun’s tidal forces, but not completely tidally locked:
Revolution period = 3/2 times rotation period
Revolution: ≈ 88 days
Rotation: ≈ 59 days

→ Extreme day-night temperature contrast: 100 K (-173 °C) – 600 K (330 °C)

Lobate Scarps

Curved cliffs, probably formed when Mercury shrank while cooling down

History of Mercury

1) Differentiation to form metallic core and rocky mantle
2) Major impact might have molten and ejected mantle
3) Massive meteorite bombardment → Cratering; lava flows

Venus

The Rotation of Venus

Almost all planets rotate counterclockwise, i.e. in the same sense as orbital motion.

Exceptions: Venus, Uranus and Pluto
Venus rotates clockwise, with period slightly longer than orbital period.

Possible reasons:
• Off-center collision with massive protoplanet
• Tidal forces of the sun on molten core
The Atmosphere of Venus

- Extremely inhospitable:
  - 96% carbon dioxide (CO₂)
  - 3.5% nitrogen (N₂)
  - Rest: water (H₂O), hydrochloric acid (HCl), hydrofluoric acid (HF)

- 4 thick cloud layers (→ surface invisible to us from Earth).
- Very stable circulation patterns with high-speed winds (up to 240 km/h).
- Very efficient “greenhouse”!
- Extremely high surface temperature up to 745 K (= 880 °F).

The Surface of Venus

- Early radar images already revealed mountains, plains, craters.
- More details from orbiting and landing spacecraft:

The Surface of Venus (II)

- Venera 13 photograph of surface of Venus:
  - Colors modified by clouds in Venus' atmosphere.
  - After correction for atmospheric color effect:

Volcanic Features on Venus

- Baltis Vallis: 6800 km long lava flow channel (longest in the solar system).
- Coroae: Circular bulges formed by volcanic activity.
- Lava flows:
  - Some lava flows collapsed after molten lava drained away.
- Pancake domes: Associated with volcanic activity forming coroae.

Craters on Venus

- Nearly 1000 impact craters on Venus’ surface:
  - → Surface not very old.
  - No water on the surface; thick, dense atmosphere
  - → No erosion
  - → Craters appear sharp and fresh.

Volcanism on Earth

- Volcanism on Earth is commonly found along subduction zones (e.g., Rocky Mountains).
- This type of volcanism is not found on Venus or Mars.
Shield Volcanoes

Found above hot spots:

Fluid magma chamber, from which lava erupts repeatedly through surface layers above.

All volcanoes on Venus and Mars are shield volcanoes

Shield Volcanoes (II)

Tectonic plates moving over hot spots producing shield volcanoes → Chains of volcanoes

Example: The Hawaiian Islands

A History of Venus

Complicated history; still poorly understood. Very similar to Earth in mass, size, composition, density, but no magnetic field → Core solid?

Solar wind interacts directly with the atmosphere, forming a bow shock and a long ion tail.

CO₂ produced during outgassing remained in atmosphere (on Earth: dissolved in water).

Any water present on the surface rapidly evaporated → feedback through enhancement of greenhouse effect

Heat transport from core mainly through magma flows close to the surface (→ coronae, pancake domes, etc.)

Mars

- Diameter = 1/2 Earth’s diameter
- Very thin atmosphere, mostly CO₂
- Rotation period = 24 h, 40 min.
- Axis tilted against orbital plane by 25°, similar to Earth’s inclination (23.5°)
- Seasons similar to Earth → Growth and shrinking of polar ice cap
- Crust not broken into tectonic plates
- Volcanic activity (including highest volcano in the solar system)

The Atmosphere of Mars

Very thin: Only 1% of pressure on Earth’s surface

95% CO₂

Even thin Martian atmosphere evident through haze and clouds covering the planet.

Occasionally: Strong dust storms that can enshroud the entire planet.

History of Mars’ Atmosphere

Atmosphere probably initially produced through outgassing.

Loss of gases from a planet’s atmosphere:

Compare typical velocity of gas molecules to escape velocity

Gas molecule velocity greater than escape velocity: → gasses escape into space.

Mars has lost all lighter gasses; retained only heavier gasses (CO₂).
The Geology of Mars

- Giant volcanoes
- Valleys
- Impact craters
- Reddish deserts of broken rock, probably smashed by meteorite impacts.

Geology of Mars (II)

- Northern Lowlands: Free of craters; probably re-surfaced a few billion years ago.
- Possibly once filled with water.
- Southern Highlands: Heavily cratered; probably 2 – 3 billion years old.

Volcanism on Mars

- Volcanoes on Mars are shield volcanoes.
- Olympus Mons: Highest and largest volcano in the solar system.

Volcanism on Mars (II)

- Tharsis rise (volcanic bulge): Nearly as large as the U.S.
- Rises ~ 10 km above mean radius of Mars.
- Rising magma has repeatedly broken through crust to form volcanoes.

Hidden Water on Mars

- No liquid water on the surface: Would evaporate due to low pressure.
- But evidence for liquid water in the past:
  - Outflow channels from sudden, massive floods
  - Collapsed structures after withdrawal of sub-surface water
  - Splash craters and valleys resembling meandering river beds
  - Gullies, possibly from debris flows
  - Central channel in a valley suggests long-term flowing water

Evidence for Water on Mars

- Hematite concretions (spheres) photographed by Mars rover Opportunity:
  - Probably crystals grown in the presence of water.
  - Layered rocks: Evidence for sedimentation
Ice in the Polar Cap

- Polar cap contains mostly CO₂ ice, but also water.
- Multiple ice regions separated by valleys free of ice.
- Boundaries of polar caps reveal multiple layers of dust, left behind by repeated growth and melting of polar-cap regions.

The Moons of Mars

- Two small moons: Phobos and Deimos.
- Too small to pull themselves into spherical shape.
- Typical of small, rocky bodies: Dark grey, low density.
- Very close to Mars; orbits around Mars faster than Mars' rotation.
- Probably captured from outer asteroid belt.
Chapter 18: Comparative Planetology of the Outer Planets

### Jupiter

Largest and most massive planet in the solar system:
- Contains almost 3/4 of all planetary matter in the solar system.
- Most striking features visible from Earth: Multi-colored cloud belts

**Jupiter’s Interior**
- From radius and mass → Average density of Jupiter ≈ 1.34 g/cm³
  - Jupiter cannot be made mostly of rock, like earthlike planets.
  - Jupiter consists mostly of hydrogen and helium.

**Aurorae on Jupiter**
- Just like on Earth, Jupiter’s magnetosphere produces aurorae concentrated in rings around the magnetic poles.
  - ~ 1000 times more powerful than aurorae on Earth.

**Jupiter’s Magnetic Field**
- Discovered through observations of decimeter (radio) radiation
- Magnetic field at least 10 times stronger than Earth’s magnetic field.
- Magnetosphere over 100 times larger than Earth’s magnetosphere.
- Extremely intense radiation belts:
  - Very high energy particles can be trapped; radiation doses corresponding to ~ 100 times lethal doses for humans!
Comet Impact on Jupiter

Impact of 21 fragments of comet Shoemaker-Levy 9 in 1994

Visualization: Impacts seen for many days as dark spots

Impacts released energies equivalent to a few megatons of TNT (Hiroshima bomb: ~0.15 megaton)

Jupiter's Atmosphere

Jupiter's liquid hydrogen ocean has no surface:

- Gradual transition from gaseous to liquid phases as temperature and pressure combine to exceed the critical point.
- Jupiter shows limb darkening → hydrogen atmosphere above cloud layers.
- Only very thin atmosphere above cloud layers;
- Transition to liquid hydrogen zone ~1000 km below clouds.

Clouds in Jupiter's Atmosphere (II)

Three layers of clouds:
1. Ammonia (NH₃) crystals
2. Ammonia hydrosulfide (NH₄SH)
3. Water crystals

The Cloud Belts of Jupiter

Dark belts and bright zones:
- Zones higher and cooler than belts; high-pressure regions of rising gas.

The Cloud Belts on Jupiter (II)

Just like on Earth, high- and low-pressure zones are bounded by high-pressure winds.

Jupiter's Ring

Not only Saturn, but all four gas giants have rings.

- Jupiter's ring: dark and reddish; only discovered by Voyager 1 spacecraft.
- Composed of microscopic particles of rocky material.
- Location: Inside Roche limit, where larger bodies (moons) would be destroyed by tidal forces.

- Ring material can't be old because radiation pressure and Jupiter's magnetic field force dust particles to spiral down into the planet.

Jupiter's cloud belt structure has remained unchanged since humans began mapping them.
Jupiter’s Family of Moons

Over two dozen moons known now; new ones are still being discovered.

Four largest moons already discovered by Galileo:

The Galilean moons

- Io
- Europa
- Ganymede
- Callisto

Interesting and diverse individual geologies.

Callisto: The Ancient Face

Tidally locked to Jupiter, like all of Jupiter’s moons.

Av. density: 1.79 g/cm³

→ composition: mixture of ice and rocks

Dark surface, heavily pocked with craters.

No metallic core: Callisto never differentiated to form core and mantle.

→ No magnetic field.

Layer of liquid water, ~ 10 km thick, ~ 100 km below surface, probably heated by radioactive decay.

Ganymede: A Hidden Past

Largest of the 4 Galilean moons. Av. density = 1.9 g/cm³

- Rocky core
- Ice-rich mantle
- Crust of ice

1/3 of surface old, dark, cratered; rest: bright, young, grooved terrain

Bright terrain probably formed through flooding when surface broke

Europa: A Hidden Ocean

Av. density: 3 g/cm³

→ composition: mostly rock and metal; icy surface.

Close to Jupiter → should be hit by many meteoroid impacts; but few craters visible.

→ Active surface; impact craters rapidly erased.

The Surface of Europa

Cracked surface and high albedo (reflectivity) provide further evidence for geological activity.

The Interior of Europa

Europa is too small to retain its internal heat → Heating mostly from tidal interaction with Jupiter.

Core not molten → No magnetic field.

Europa has a liquid water ocean ~ 15 km below the icy surface.
Io: Bursting Energy

Most active of all Galilean moons; no impact craters visible at all.

Over 100 active volcanoes!

Activity powered by tidal interactions with Jupiter.

Av. density = 3.55 g/cm³ → Interior is mostly rock.

The History of Jupiter

• Formed from cold gas in the outer solar nebula, where ices were able to condense.
• Rapid growth
• Soon able to trap gas directly through gravity
• Heavy materials sink to the center
• Dust from meteorite impacts onto inner moons trapped to form ring

Saturn

Mass: ~ 1/3 of mass of Jupiter
Radius: ~ 16% smaller than Jupiter
Av. density: 0.69 g/cm³ → Would float in water!

Rotates about as fast as Jupiter, but is twice as oblate → No large core of heavy elements.
Mostly hydrogen and helium; liquid hydrogen core.
Saturn radiates ~ 1.8 times the energy received from the sun. Probably heated by liquid helium droplets falling towards center.

Saturn’s Atmosphere

Three-layered cloud structure, just like on Jupiter
Main difference to Jupiter:
Fewer wind zones, but much stronger winds than on Jupiter:
Winds up to ~ 500 m/s near the equator!

Saturn’s Rings

Ring consists of 3 main segments:
A, B, and C Ring
separated by empty regions:
divisions
Rings can’t have been formed together with Saturn because material would have been blown away by particle stream from hot Saturn at time of formation.

Composition of Saturn’s Rings

Rings are composed of ice particles
moving at large velocities around Saturn, but small relative velocities (all moving in the same direction).
Shepherd Moons

Some moons on orbits close to the rings focus the ring material, keeping the rings confined.

Divisions and Resonances

Moons do not only serve as “shepherds”. Where the orbital period of a moon is a small-number fractional multiple (e.g., 2:3) of the orbital period of material in the disk (“resonance”), the material is cleared out → Divisions

Electromagnetic Phenomena in Saturn’s Rings

Radial spokes in the rings rotate with the rotation period of Saturn:

Titan: Saturn’s Largest Moon

About the size of Jupiter’s moon Ganymede.
Rocky core, but also large amount of ice.
Thick atmosphere, hiding the surface from direct view.

Titan’s Atmosphere

Because of the thick, hazy atmosphere, surface features are only visible in infrared images.
Many of the organic compounds in Titan’s atmosphere may have been precursors of life on Earth.
Surface pressure: 50% greater than air pressure on Earth
Surface temperature: 94 K (-290 °F)
→ Methane and ethane are liquid!
Methane is gradually converted to ethane in the Atmosphere
→ Methane must be constantly replenished, probably through breakdown of ammonia (NH₃).

Saturn’s Smaller Moons

Saturn’s smaller moons formed of rock and ice; heavily cratered and appear geologically dead.

Tethys:
Heavily cratered; marked by 3 km deep, 1500 km long crack.

Iapetus:
Leading (upper right) side darker than rest of surface because of dark deposits.

Enceladus:
Possibly active; regions with fewer craters, containing parallel grooves, possibly filled with frozen water.
Uranus

- 1/3 the diameter of Jupiter
- 1/20 the mass of Jupiter
- no liquid metallic hydrogen
- Deep hydrogen + helium atmosphere

The Motion of Uranus

- Orbit slightly elliptical; orbital period ≈ 84 years.
- Very unusual orientation of rotation axis. Almost in the orbital plane.
- Possibly result of impact of a large planetesimal during the phase of planet formation.
- Large portions of the planet exposed to “eternal” sunlight for many years, then complete darkness for many years!

The Atmosphere of Uranus

- Like other gas giants: No surface.
- Gradual transition from gas phase to fluid interior.
- Mostly H; 15% He, a few % methane, ammonia and water vapor.
- Optical view from Earth: Blue color due to methane, absorbing longer wavelengths

Cloud Structures of Uranus

- Possibly due to seasonal changes of the cloud structures.

The Rings of Uranus

- Rings of Uranus and Neptune are similar to Jupiter’s rings.
- Confined by shepherd moons; consist of dark material.
- Apparent motion of star behind Uranus and rings
- Rings of Uranus were discovered through occultations of a background star

The Rings of Neptune

- Made of dark material, visible in forward-scattered light.
- Ring material must be regularly re-supplied by dust from meteorite impacts on the moons.
- Interrupted between denser segments (arcs)
- Focused by small shepherd moons embedded in the ring structure.
**The Moons of Uranus**

5 largest moons visible from Earth.

10 more discovered by Voyager 2; more are still being found.

Dark surfaces, probably ice darkened by dust from meteorite impacts.

5 largest moons all tidally locked to Uranus.

**The Moons of Neptune**

Two moons (Triton and Nereid) visible from Earth;
6 more discovered by Voyager 2

Unusual orbits:
- Triton: Only satellite in the solar system orbiting clockwise, i.e., "backward".
- Nereid: Highly eccentric orbit; very long orbital period (359.4 d).

**The Atmosphere of Neptune**

Cloud-belt structure with high-velocity winds; origin not well understood.

Darker cyclonic disturbances, similar to Great Red Spot on Jupiter, but not long-lived.

White cloud features of methane ice crystals

**The Surface of Triton**

Very low temperature (34.5 K)

- Triton can hold a tenuous atmosphere of nitrogen and some methane; 10^3 times less dense than Earth's atmosphere.
- Surface composed of ices: nitrogen, methane, carbon monoxide, carbon dioxide.
- Possibly cyclic nitrogen ice deposition and re-vaporizing on Triton's south pole, similar to CO₂ ice polar cap cycles on Mars.

Dark smudges on the nitrogen ice surface, probably due to methane rising from below surface, forming carbon-rich deposits when exposed to sunlight.

**The Surface of Triton (II)**

Ongoing surface activity:
- Surface features probably not more than 100 million years old.
- Large basins might have been flooded multiple times by liquids from the interior.
- Ice equivalent of greenhouse effect may be one of the heat sources for Triton's geological activity.
Pluto as a Planet
• Virtually no surface features visible from Earth.
  • ~ 65% of size of Earth’s Moon.
• Highly elliptical orbit; coming occasionally closer to the sun than Neptune.
• Orbit highly inclined (17°) against other planets’ orbits
  → Neptune and Pluto will never collide.
• Surface covered with nitrogen ice; traces of frozen methane and carbon monoxide.
• Daytime temperature (50 K) enough to vaporize some N and CO to form a very tenuous atmosphere.

Pluto’s Moon Charon
Discovered in 1978; about half the size and 1/12 the mass of Pluto itself.
Tidally locked to Pluto.

Pluto and Charon
Orbit highly inclined against orbital plane.
From separation and orbital period:
\[ \text{M}_{\text{pluto}} \approx 0.2 \text{ Earth masses}. \]
\[ \text{Density} \approx 2 \text{ g/cm}^3 \]
(both Pluto and Charon)
\[ \rightarrow \text{ ~ 35% ice and 65% rock.} \]
Large orbital inclinations → Large seasonal changes on Pluto and Charon.

The Origin of Pluto and Charon
Probably very different history than neighboring jovian planets.
Older theory: Pluto and Charon formed as moons of Neptune, ejected by interaction with massive planetesimal. Mostly abandoned today since such interactions are unlikely.
Modern theory: Pluto and Charon members of Kuiper belt of small, icy objects (see Chapter 25).
Collision between Pluto and Charon may have caused the peculiar orbital patterns and large inclination of Pluto’s rotation axis.