Planets and their Interior

Ulrich Christensen
Max-Planck-Institut für Sonnensystemforschung
Katlenburg-Lindau
The family

Mercury 5262 km  
Venus 5150 km  
Earth 4880 km  
Mars 4806 km  
Jupiter 3642 km  
Saturn 3476 km  
Uranus 3138 km  
Neptune 2706 km  
Pluto 2300 km  
Titania 1580 km
The Moon

Bright, heavily cratered, highland regions versus dark, smooth Mare regions with much lower crater density. Highland = primitive crust of the Moon, > 4 Gyr old. Mare = volcanic flood basalts filling impact depressions, 3.3 – 3.8 Gyr old.

Crater density serves as measure for the age of the surface on planets from which we have no samples, with the moon taken for calibration.
Moon’s interior

Radius: 1737 km
Mean density: 3340 kg m⁻³: not much higher than density of Earth’s mantle rock ⇒ metallic core radius <400 km. Small core is likely.

Seismic information: weak moonquakes, shallow and deep (down to ~ 1000 km). Travel times: Crustal thickness 30 – 50 km, strong damping of waves below 1000 km ⇒ soft mantle at depth

Favored hypothesis on origin of the moon: giant impact of Mars-size body into proto-Earth splashed away mostly mantle material that recondensed in orbit to form the Moon.
Mercury

Radius = 2,400 km  (38% Earth)
ρ_{mean} = 5440 kg m^{-3}  (98% Earth)
T_{rot} ≈ 59 d = 2/3 T_{orbit}

45% of Mercury‘s surface have been imaged in 1974/75 by Mariner 10. It is heavily cratered ⇒ age > 4 \times 10^9 \text{ yr.}

Weak global magnetic field ⇒ dynamo in fluid iron core.
Mercury

No signs of plate tectonics

„Lobate scarps“ (compressional faults) interpreted as signs of global planet contraction by $\approx 2$ km.
Simple structural models for terrestrial planets: mantle and core

Assume that all the terrestrial planets are composed of a silicate mantle (with similar composition as Earth's mantle) and an iron core (with some light element). Fixing plausible densities for the mantle and core ($\rho_M \approx 3200-3500 \text{ kgm}^{-3}$, $\rho \approx 6500–7800 \text{ kgm}^{-3}$ at low pressure), the core radius is calculated by matching the mean density (= mass/volume) obtained from the planets gravity. To account for the pressure effect, an „uncompressed density“ is estimated.

<table>
<thead>
<tr>
<th></th>
<th>Density [kgm^{-3}]</th>
<th>Uncompr. density</th>
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</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5420</td>
<td>5280</td>
</tr>
<tr>
<td>Venus</td>
<td>5250</td>
<td>3990</td>
</tr>
<tr>
<td>Earth</td>
<td>5515</td>
<td>4060</td>
</tr>
<tr>
<td>Moon</td>
<td>3340</td>
<td>3315</td>
</tr>
<tr>
<td>Mars</td>
<td>3940</td>
<td>3720</td>
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</tbody>
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Mercury has the highest uncompressed density, hence the largest relative core size (≈75% of planetary radius). The Moon is relatively smallest core.
Venus

Radius: 6080 km (95% $R_{\text{Earth}}$)
Slow rotation: $T = 225$ d

Atmospheric pressure: 90 bar
Temperature: 450°C

Main constituent: $\text{CO}_2$ (95%)
Clouds: $\text{H}_2\text{SO}_4$ droplets

Surface: Basaltic rocks
Venus

Global topographic map

No bimodal height distribution (as in case of Earth) $\Rightarrow$ no continent – ocean dichotomy. No clear signs of plate tectonics.

Many signs of volcanism.
Venus

Global distribution of impact craters

Crater density statistically uniform ⇒ different surface units have similar age. Crater density much lower than on Moon / Mercury ⇒ surface age ≈ 500 Myr. Few craters are tectonically overprinted or embayed by lava flows.

Global re-surfacing event (flooding by lavas) about 500 Myr ago ?
Mars

Radius: 3370 km (53% Earth)
Rotation period: 24 h 56 min
CO₂-atmosphere: 6 mbar, -40°C
Seasonal condensation of CO₂ in polar regions.

Running water in early history.
Water ice present in polar regions.
Mars: Topography & Geoid

Southern highlands: heavily cratered: > 4 Gyr old
Northern lowlands: 2 – 4 Gyr (a few regions very young)
Tharsis bulge with giant volcanoes (2 – 4 Gyrs)

North-south dichotomy and Hellas basin not associated with gravity anomaly: shallow compensation (crust thickness variation)
Tharsis bulge associated with strong gravity anomaly: deep origin
Mars: Volcanism

Tharsis volcanoes are the largest volcanoes in the solar system. Olympus mons summit caldera is young $\Rightarrow$ active volcanism

Volcanism concentrated on Tharsis region $\Rightarrow$ single large mantle plume Mars below Tharsis?
Mars: Magnetic field

No global magnetic field, but strong local magnetic "anomalies" in parts of the southern highlands ⇒ did Mars have an early, now extinct, dynamo?
Moment of inertia factor

When the (zero-pressure) density of mantle rock and of core material are not fixed, the mean density is not enough to constrain the size of the core. What other constraints do we have?

<table>
<thead>
<tr>
<th>Mean density</th>
<th>Moment of inertia (MoI) factor</th>
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<tbody>
<tr>
<td>$\bar{\rho} = 4\pi \int \rho(r) \ r^2 \ dr$</td>
<td>$\frac{C}{Ma^2} = 2 \int \frac{\rho(r)}{\bar{\rho}} \ r^4 \ dr$</td>
</tr>
</tbody>
</table>

$C/ Ma^2$ is sensitive to the radial distribution of mass – for a uniform sphere it is 0.4; for a body with a core with radius $a/2$ and $\rho_c = 2\rho_m$ it is 0.347.

$C/ Ma^2$ can be determined from (1) the perturbation of the gravity field resulting from the rotational flattening of the planet plus (2a) the assumption of a hydrostatic shape of the planet (where it is justified) or (2b) observation of the precession (or libration) of the planet.

For the Earth $C/ Ma^2 = 0.3308$, for Mars 0.365.

Symbols: $\rho$ – density ($\rho_m, \rho_c$ – of mantle/core), $r$ – radius, $a$ – planet’s radius, $C$ – polar moment of inertia, $M$ – planet’s mass
Models of the Martian Interior

When both the mantle composition - MgO/(FeO+MgO) ratio – and the core composition (FeS-content) are treated as free parameters, together with the core radius, a range of models is possible (3 unknowns, 2 constraints).

Models with a small high-density core or a large low-density core are compatible with the mean density and the MoI.

The mantle contains more iron (FeO) than Earth’s mantle.

Because of lower gravity, phase transitions occur at greater depth than in the Earth. Unclear if transition to perovskite occurs at all.

Observation of response to tidal forcing: (partly) liquid core with 1500 - 1800 km.
Jupiter: a gas giant

Radius: 71,400 km (10 x Earth)
Mean density: 1330 kg m⁻³
Rotation period: 10 h
Atmospheric composition:
85% H₂, 14% He, small amounts of NH₃ and other components form clouds
Very dynamic atmosphere
Emitted energy 70% higher than absorbed sunlight ⇒ 5 W/m² internal heat flow
**Jupiter: magnetic field**

Dipole-dominated magnetic field
Field strength 10x Earth's field
Tilt of dipole ≈ 10°

⇒ Active dynamo in Jupiter
Jupiter: Interior structure

Models of the interior are based on

- Mean density
- Moment of inertia and higher gravity moments
- Assumption of hydrostatic equilibrium
- Assumption of adiabatic temperature
- Equation of state of H – He mixtures

- Molecular hydrogen in outer shell
- Metallic hydrogen in deep shell (to 85% of radius with transition region \(\Rightarrow\) seat of dynamo)
- Core of rock and iron likely (on the order of 10 Earth masses = 3% of Jupiter mass)
Jupiter: zonal flow

Strong zonal winds are associated with the latitudinal zones and bands, with velocities up to 150 m/sec, alternating in direction. The zonal velocity is larger than the velocity of the superimposed eddies. Wind speed and pattern has hardly changed in 25 yr.

Two competing concepts for the origin of the zonal flow:

(1) Meteorological phenomenon of a shallow atmospheric layer, powered by solar heat.

(2) Expression of convection in the deep interior, driven by Jupiter's internal heat.

Observation by the Galileo probe that the wind speed does not decrease with depth below the cloud deck (up to the 20 bar pressure level) supports 2nd hypothesis.
Galilean Satellites

Io
Europa
Ganymede
Callisto
Moon
Galilean satellites: surfaces

Io - No impact craters. Volcanically most active object in solar system. Heat flow 2 W/m² (20 x Earth), supplied by tidal friction from large tides (~30 m) excited by massive Jupiter.

Europa - Very few impact craters. In some places fractured surface looking like pack-ice rafts that drifted on fluid substratum. Active interior, surface 50 Myr old (?)

Ganymede & Callisto Many impact craters (surface age > 4 Gyr). Impacts removed dark surface material and excavated bright interior. Surface material ice (+ dust).
Galilean satellites: interior

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<tr>
<th></th>
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<th>$C/Ma^2$</th>
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<tbody>
<tr>
<td>Io</td>
<td>3530</td>
<td>0.378</td>
</tr>
<tr>
<td>Europa</td>
<td>3020</td>
<td>0.347</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1940</td>
<td>0.311</td>
</tr>
<tr>
<td>Callisto</td>
<td>1850</td>
<td>0.358</td>
</tr>
</tbody>
</table>

From close flybys mean density and $M$-factors (assume hydrostatic shape)

Low density of outer satellites $\Rightarrow$ substantial ice ($H_2O$) component.

Three-layer models (ice, rock, iron) except for Io, assuming rock/Fe ratio.

Possibly deep liquid water ocean below ice.

Intrinsic magnetic field of Ganymede $\Rightarrow$ dynamo in iron core or salty ocean.

Callisto's $M$ too large for complete differentiation $\Rightarrow$ core rock-ice mixture.

Like silicate rock in mantles of terrestrial planets, solid ice can convect slowly at temperatures not too far below melting point.
### Saturn, Uranus, Neptune

<table>
<thead>
<tr>
<th></th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
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<tbody>
<tr>
<td>$\rho$ [kg m$^{-3}$]</td>
<td>704</td>
<td>1290</td>
<td>1650</td>
</tr>
<tr>
<td>$a$ [km]</td>
<td>60,200</td>
<td>25,900</td>
<td>24,800</td>
</tr>
</tbody>
</table>

**Saturn** is the little brother of Jupiter: Mainly composed of H+He; strong alternating zonal jet flow at the surface; magnetic field very dipolar.

**Uranus** and **Neptune** are different: Surface CH$_4$ in addition to H+He. Smaller size but higher mean density than Saturn $\Rightarrow$ must consist mainly of denser components. Strong zonal wind flow retrograde at equator.
Uranus, Neptune: Ice giants

Mainly $\text{H}_2 + \text{He}$  
„Ices“ ($\text{H}_2\text{O}$, $\text{NH}_3$, $\text{CH}_4$)  
Rocky core ($\sim 1\ M_{\text{earth}}$)

Interior consists mainly of supercritical fluid composed of water, ammonia and other components. It is an ionic conductor and dynamos are thought to operate in this region.

Radial component of Neptune's magnetic field. $\sim 50\%$ of Earth's field strength, dipole strongly tilted and significant non-dipole components (Uranus' field qualitatively similar).