Planetary Interiors
Interiors

- How might we learn about the interior structure of the Earth, or other planets?
  - What observations can you make to do this?
Densities

• A good guess to the composition can be obtained from the mean “bulk” density (i.e., by measurement of M & R)
• Since planetary interiors are under great pressure, the densities are greater than the “standard”, uncompressed densities of the component elements.

<table>
<thead>
<tr>
<th>Planet</th>
<th>$\rho_{bulk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5430kg/m$^3$</td>
</tr>
<tr>
<td>Venus</td>
<td>5240</td>
</tr>
<tr>
<td>Earth</td>
<td>5520</td>
</tr>
<tr>
<td>Moon</td>
<td>3360</td>
</tr>
<tr>
<td>Mars</td>
<td>3940</td>
</tr>
</tbody>
</table>

• Mercury has the highest content of dense elements (Fe, Mg)
• Moon and Mars have uncompressed densities similar to various silicates. Low fraction of iron and other metals.
Densities

• If we can measure the densities of surface rocks, we can tell something about how differentiated a planet is
  ➢ On small asteroids, the surface rock has density similar to the bulk density. They have a relatively uniform composition.
  ➢ Moon: surface rocks have density of ~2800 kg/m$^3$. Indicates the possibility of an iron core
  ➢ Earth surface rocks also have density of ~2800 kg/m$^3$. There must be much more iron in the interior.

<table>
<thead>
<tr>
<th>Planet</th>
<th>$\rho_{\text{bulk}}$</th>
<th>$\rho_{\text{unc}}$</th>
<th>$\rho_{\text{unc}}/\rho_{\text{bulk}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5430 kg/m$^3$</td>
<td>5300 kg/m$^3$</td>
<td>0.976</td>
</tr>
<tr>
<td>Venus</td>
<td>5240</td>
<td>4000</td>
<td>0.763</td>
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<tr>
<td>Earth</td>
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<td>4100</td>
<td>0.743</td>
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<tr>
<td>Moon</td>
<td>3360</td>
<td>3300</td>
<td>0.982</td>
</tr>
<tr>
<td>Mars</td>
<td>3940</td>
<td>3700</td>
<td>0.939</td>
</tr>
</tbody>
</table>
Plastic flow

• Under pressure, even solid rock can deform, and “flow”
• Thus solid also obeys the equation of hydrostatic equilibrium:

\[ dP = - \frac{GM(r)}{r^2} \rho dr \]

• Dense material is likely to flow downward, while lighter material rises
• The density actually does not vary too much within a planet (because rock isn’t too compressible).

\[ P(r) \approx \frac{2\pi G}{3} \rho^2 R^2 \left( 1 - \left( \frac{r}{R} \right)^2 \right) \]
• Under high enough pressures, the density of rock increases strongly as it undergoes “phase changes”
  ➢ E.g. carbon under high pressure becomes diamond
  ➢ Olivine becomes spinel and causes a sharp increase in density about 400 km within the Earth.
The moment of inertia is a measure of degree of concentration

- Related to the “inertia” (resistance) of a spinning body to external torques
- Can therefore be measured by observing how rotation responds to torques exerted by the Sun and large planets or moons.
- Torques from the Sun and moon cause the axis of Earth’s rotation to precess

<table>
<thead>
<tr>
<th>Body</th>
<th>I/MR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>0.06</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.33</td>
</tr>
<tr>
<td>Venus</td>
<td>0.33</td>
</tr>
<tr>
<td>Earth</td>
<td>0.33</td>
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<tr>
<td>Moon</td>
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<tr>
<td>Mars</td>
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<tr>
<td>Jupiter</td>
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<tr>
<td>Saturn</td>
<td>0.210</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.23</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Earth’s rotation axis in approximately AD 14,000
Magnetic fields

• The presence of a magnetic field most likely indicates the presence of a molten, rapidly rotating, conducting (e.g., iron) core.

<table>
<thead>
<tr>
<th>Object</th>
<th>Magnetic Field (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>200,000</td>
</tr>
<tr>
<td>Mercury</td>
<td>220</td>
</tr>
<tr>
<td>Venus</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Earth</td>
<td>30,500</td>
</tr>
<tr>
<td>Moon (3.3 Gyr ago)</td>
<td>2000</td>
</tr>
<tr>
<td>Moon (today)</td>
<td>10</td>
</tr>
<tr>
<td>Mars</td>
<td>40</td>
</tr>
<tr>
<td>Jupiter</td>
<td>420,000</td>
</tr>
<tr>
<td>Saturn</td>
<td>20,000</td>
</tr>
<tr>
<td>Uranus</td>
<td>23,000</td>
</tr>
<tr>
<td>Neptune</td>
<td>100,000</td>
</tr>
</tbody>
</table>

• Moon and Mars are small and have probably entirely cooled, so they no longer have a molten core.
• Venus rotates very slowly, but is this enough to explain the absence of a field?
• Why is Mercury so strong?
• Jupiter and Saturn rotate rapidly, and have metallic hydrogen inner mantles
Seismology

- Vibrations on the surface can send sound waves through the interior
  - Pressure waves compress the material along the direction of motion, and can pass through solid or liquid material (longitudinal waves)
  - Shear waves move material up and down, and are only present in solid material (transverse waves)
Seismology

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Wave motion

- Waves that originate at a point spread out in all directions.
- We can represent the motion with lines that connect successive “crests” of the wave.
- The velocity of the wave depends on the sound speed of the medium.
- If the waves arrive obliquely at the boundary, the change in speed results in a change in direction. This is known as refraction.
• There is an area on the surface where no P- or S- waves are detected
  ➢ This is the *shadow zone* and proves that the Earth does not have a homogeneous composition
  ➢ There must exist a core in which the sound speed is slower
Seismology

- Direct S-waves are only detected over a little more than half of the Earth’s surface.
- An inner, molten core must exist.
- Must be hot (>4000 K)
Earth’s interior

- **Crust**: thin layer of low-density rock
- **Mantle**: can be directly studied via magma erupted by volcanoes.
  - Mostly made of pyrolite, with an uncompressed density of \(~3300\ \text{kg/m}^3\).
- **Core**: Can work out the mass of Earth’s core, assuming its size and density, or from a two layer model and the bulk and constituent densities (often the way this is done for KBOs).
Interior temperature of Earth

- Melting temperature increases with pressure
- Pressure in core is so high that it may be solid material
Moonquakes

- Five seismographs were placed by Apollo astronauts.
- Shallow quakes mainly due to impacts.
- Deep quakes never deeper than ~1000 km; deep mantle is "soft."
- Any iron core must be much smaller than Earth's (<4% iron by mass).
If we assume the structure of the terrestrial planets are approximately similar, we can deduce the relative sizes of the core, mantle and crust from measurements of the mean density.
Sources of internal heat

- Most planets and moons were probably mostly molten when they first formed
  - There is evidence that the moon was covered by a magma ocean 4.5 Gyr ago
Sources of Heat

• Radiogenic Heating
  • Decay of short-lived radioactive species can release substantial amounts of heat (e.g., Aluminum 26, Iron isotopes)
  • Most of heat is released in a few half-lives of the species (e.g., ~1-3Myr after formation in supernovae).
  • This constrains when radiogenic heat can function.

• Gravitational Heating
  • Heat released in assembling object (e.g. Impact heating, giant impacts).
  • Equal to gravitational binding energy ($E = -3GM^2/5R$ - constrains amount of heating)
  • Heat release occurs during formation epoch (can be after ~3Myr).
Sources of Heat

- Tidal Heating
  - Primarily due to orbital eccentricity and small orbit (i.e., being near tidal perturber).
  - This damps eccentricity to zero; $e \rightarrow 0$ and heating decreases
  - Orbital resonances can excite eccentricity and maintain tidal heating over long times (e.g., Io, Europa, Enceladus?).
  - Tidal heating is limited by eccentricity and orbital configurations (e.g., tidal evolution through mean motion resonances).
The Earth’s mantle has a thermal conductivity of ~ 1 W/m/K. Radioactive decay heats the core to about 5000 K. The rate of heat loss at the surface can be calculated and compared to the solar constant.
Evolution of Shape and Interior

- Bodies with Rock/Ice strength ($S$) greater than internal pressure ($P(r)$) may support irregular shapes. $P(r) < S$
- Bodies that are melted tend to differentiate and become spherical (the minimum energy config). A fluid has no real material strength
- Differentiation is indicative of global melting.
- Irregular shapes suggest that the body – as it is observed now has not been melted (at least since the shape was determined) and is not in hydrostatic equilibrium.
Other terrestrial interiors

**Moon**
- Small, old iron core
- Cooled quickly, and lithosphere thickened to 1000-km.

**Mercury**
- Large iron core, at least partially molten (B-field)

**Venus:**
- May have smaller core than earth, with less FeS
- No magnetic field, plate tectonics

**Mars**
- Large core has a lot of sulfur, and is mostly liquid
Icy satellites of outer planets

Callisto (R=2403km)
- highest ice content. Never-melted, undifferentiated interior.

Ganymede (R=2634km)
- Highly differentiated
- May be heated

Europa (R=1565km)
- Heated enough to erupt and resurface with ice

Io (R=1821km)
- Strongly tidally heated
- Dense: no ice
Dwarf Planet Interiors

- Are the interiors of Dwarf planets and KBOs differentiated?
- Are their shapes due to the hydrostatic pressure or accretional melting?
- Ceres/Vesta – differentiated by gravity or radiogenic heat?
- Pluto, Haumea, Eris – evidence from spectra (ice of different types) and bulk density (>~1200-2600 kg/m³)
Summary of interiors
Gravity Field

• An interesting observation of the gravity field on Earth shows that it is quite uniform over the surface: it has about the same value over mountain ranges as it does over the oceans.
  ➢ Due to *isostatic equilibrium*: a floating substance displaces its own weight in material
  ➢ Lighter, crustal rock is floating on the higher density lithosphere