Terrestrial World Surfaces

- Solid rocky surfaces shaped (to varying degrees) by:
  - Impact cratering
  - Volcanism
  - Tectonics (gross movement of surface by interior forces)
  - Erosion (by impacts or by weather)
Impact Cratering

- Small bodies in the Solar System can strike larger bodies at tremendous speed (many kilometers per second).
- The tremendous energy of motion gets converted into an explosion at the point of contact.
  - Large impactors don't "gouge" they *detonate*.
  - Large craters are round independent of the angle of impact.
Impact Cratering

- Small bodies in the Solar System can strike larger bodies at tremendous speed (many kilometers per second).
- The tremendous energy of motion gets converted into an explosion at the point of contact.
  - Large impactors don't “gouge” they *detonate*.
  - Large craters are round independent of the angle of impact.
Impact Cratering

- Upon impact the surface temporarily behaves like a liquid.
  - Cratering can be reminiscent of tossing a rock in a pond.
    - Craters can have central mountain peaks.
    - Large impacts form multi-ring basins
Impact Cratering

- Upon impact the surface temporarily behaves like a liquid.
  - Cratering can be reminiscent of tossing a rock in a pond.
  - Craters can have central mountain peaks.
  - Large impacts form multi-ring basins
Impact Cratering

- Upon impact the surface temporarily behaves like a liquid.
  - Cratering can be reminiscent of tossing a rock in a pond.
    - Craters can have central mountain peaks.
    - Large impacts form multi-ring basins.
Impact Cratering

- Upon impact the surface temporarily behaves like a liquid.
  - Cratering can be reminiscent of tossing a rock in a pond.
    - Craters can have central mountain peaks.
    - Large impacts form multi-ring basins
Impact Cratering

Craters on Venus
Impact Cratering

• Upon impact the surface temporarily behaves like a liquid.
  – Cratering can be reminiscent of tossing a rock in a pond.
    • Craters can have central mountain peaks.
    • Large impacts form multi-ring basins
Impact Cratering

- Upon impact the surface temporarily behaves like a liquid.
  - Cratering can be reminiscent of tossing a rock in a pond.
    - Craters can have central mountain peaks.
    - Large impacts form multi-ring basins

Caloris Basin on Mercury
Ejecta Blankets

- Impacts splash out material that blankets surrounding terrain.
Ejecta Blankets

- Impacts splash out material that blankets surrounding terrain.
Terrestrial World Surfaces

- For the Moon...
- Solid rocky surfaces shaped (to varying degrees) by:
  - Impact cratering
  - Volcanism (lava floods within Maria)
  - Tectonics (gross movement of surface by interior forces)
  - Erosion (via impact grinding, not atmospheric)
Geological Activity vs. Planetary Size

- It's no coincidence that the smallest worlds above are the ones that are heavily cratered.
- The larger a world is the more readily it retains its internal heat.
  - A pea cools off much more quickly than a potato
- Earth and Venus are still hot in the interior and molten material can reach and re-surface the surface.
Geological Activity vs. Planetary Size

- Planets start out hot and generate heat internally through radioactive decay.
- The larger a world is the more readily it retains its internal heat.
  - A pea cools off much more quickly than a potato
- Earth and Venus are still hot in the interior and molten material can reach and re-surface the surface.
Two Extremes: Rampant Volcanism vs. Early Geological Death
It's no coincidence that the smallest worlds above are the ones that are heavily cratered.

The larger a world is the more readily it retains its internal heat.

- A pea cools off much more quickly than a potato

Earth and Venus are still hot in the interior and molten material can reach and re-surface the surface.
Geologic Activity on Earth and Venus
Geologic Activity on Earth and Venus
Mercury

- Being small, it ended geological activity relatively early and is a heavily cratered world.
Mercury

- Being small, it ended geological activity relatively early and is a heavily cratered world.
Mercury

- Possibly not as heavily cratered as the lunar highlands because it took longer to cool.
MESSENGER

- We now have an active mission orbiting Mercury and exploring it in detail.
MESSENGER

- Confirming evidence for ice at the poles

Earth-based radar view of high reflectivity regions at Mercury's north pole

MESSENGER view showing shadowed craters at the pole.
MESSENGER

- Confirming evidence for ice at the poles

Earth-based radar view of high reflectivity regions at Mercury's north pole
We now have an active mission orbiting Mercury and exploring it in detail. Signs of “recent” volcanism
Mercury

- There is evidence that Mercury shrank (only a couple of kilometers) as it cooled - lobate scarps.
  - These are “wrinkles” in the solidified surface due to shrinkage.

Mercury's rotation has been slowed by Solar tides

Mercury rotates three times for every two trips around the Sun
A World of Extremes

- Intense sunlight bakes to dayside of Mercury to temperatures of about 700K (800F).
- The nightside cools to the emptyness of space during the long nights with no atmospheric blanket. Temperatures are typically less than 100K (-280F).
Planetary Interiors – Mean Density

- It's easy to measure the average density of a planet
  - Find a satellite and determine the planet's mass
  - Divide by the planet's volume.
Planetary Interiors – Mean Density

- Ignoring the gas giants for the moment, there are three building materials out there:
  - Metal – 8 grams/cubic centimeter
  - Rock – 3 grams/cubic centimeter
  - Ice – 1 gram/cubic centimeter

These materials were available in different relative abundance depending on distance from the Sun:

close: rock and metal

far: ICE, rock, and metal
Planetary Interiors – Mean Density

• The mean density of Earth is 5.5 g/cm$^3$
  - This density is between rock and metal
  - The Earth's interior is a mix of metal and rock

• The Earth's interior is “differentiated”
  - The dense metal has sunk to the center
  - Seismic studies reveal this internal structure.
Planetary Interiors – A Differentiated Earth

Earthquake

$P$ and $S$ waves

$P$ waves

$S$ wave shadow (no $S$ waves)

Inner core

Liquid core

Mantle
Icy Moons

- The satellites of the outer planets typically have density of less than 2 grams/cm$^3$.
  - They are mostly made of water/ice and have differentiated rocky cores.
Mercury's Interior

- Although it has nearly identical density to Earth, Mercury is thought to have a proportionally larger iron core.
  - Compression of materials deep inside a planet artificially increases the density.
  - Earth doesn't need as much iron to match Mercury's density.
The density of the Moon is 3.3 grams per cubic centimeter – implying a composition that is almost entirely rock.

- Therein begins the mystery....
Lunar Puzzles

- Despite it's proximity to Earth and the likelihood that it formed at the same time and in the same place as Earth, the Moon is fundamentally different.

- Difference 1: The Moon's density indicates that it is almost entirely rock. It is lacking the iron that dominates the Earth's core.
Lunar Puzzles

- Despite its proximity to Earth and the likelihood that it formed at the same time and in the same place as Earth, the Moon is fundamentally different.

- Difference 2: Moon material has been baked to high temperature driving off most volatile compounds (e.g. water).
Lunar Puzzles

- Despite it's proximity to Earth and the likelihood that it formed at the same time and in the same place as Earth, the Moon is fundamentally different.

- **Big similarity** - The Earth and Moon have identical relative abundance of the different isotopes – oxygen 16, 17, and 18 in particular.
  - This ratio is a fingerprint of the location of formation of an object.
  - So... The Earth and Moon are completely different, yet they seem to have formed in the same place.
Theories of Lunar Formation

- **Co-formation** – The Earth and Moon grew from the Solar Nebula via accretion in the same place at the same time.
  - Supported by Oxygen isotopes
  - Not consistent with the compositional difference between Earth and Moon (lack of iron in the Moon).

- **Capture** – The Moon formed where iron was not as abundant and was subsequently captured into Earth orbit.
  - Oxygen isotopes say that this did not happen.
  - Gravitational capture is not practical – The Moon does not have retrorockets to slow it down.
  - “Baking” unexplained

- **Fission** – The Earth forms and then somehow, maybe from excessive spin, the Moon is flung out from Earth's mantle.
  - Spin (angular momentum) is conserved. There's not enough spin in the current Earth/Moon system to support this idea.
  - “Baking” unexplained.
Moon Formation in a Catastrophic Collision

- Explains everything, especially the extra “baking”
- Recall that these late giant collisions are a natural consequence of Solar System formation.
Moon Formation in a Catastrophic Collision

• The speed and direction of this collision has to be fairly exact in order to produce the Moon.
  – “Earth's” with big moons are probably rare.
Consequences of a Rare Moon

• Is the Moon a factor, maybe an important one, in complex/intelligent life arising on this world?
  – If important, worlds with complex life may be quite rare.

• Effects
  – Big alteration in initial chemistry/evolution of the Earth's surface.
Consequences of a Rare Moon

• Is the Moon a factor, maybe an important one, in complex/intelligent life arising on this world?
  - If important, worlds with complex life may be quite rare.

• Effects
  - Big tides, especially at the outset
Consequences of a Rare Moon

- Is the Moon a factor, maybe an important one, in complex/intelligent life arising on this world?
  - If important, worlds with complex life may be quite rare.
- Effects
  - A stable tilt for the Earth's axis