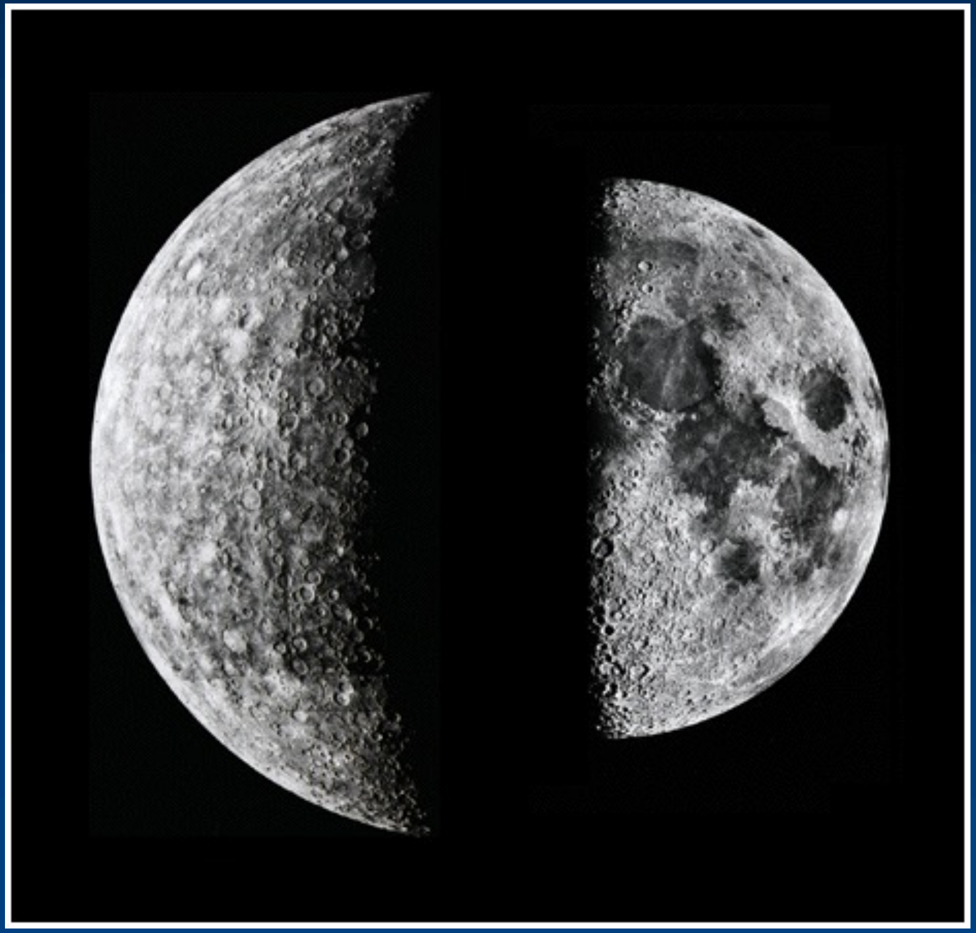
Announcements

- HW8 Due April 4

Moon and Mercury



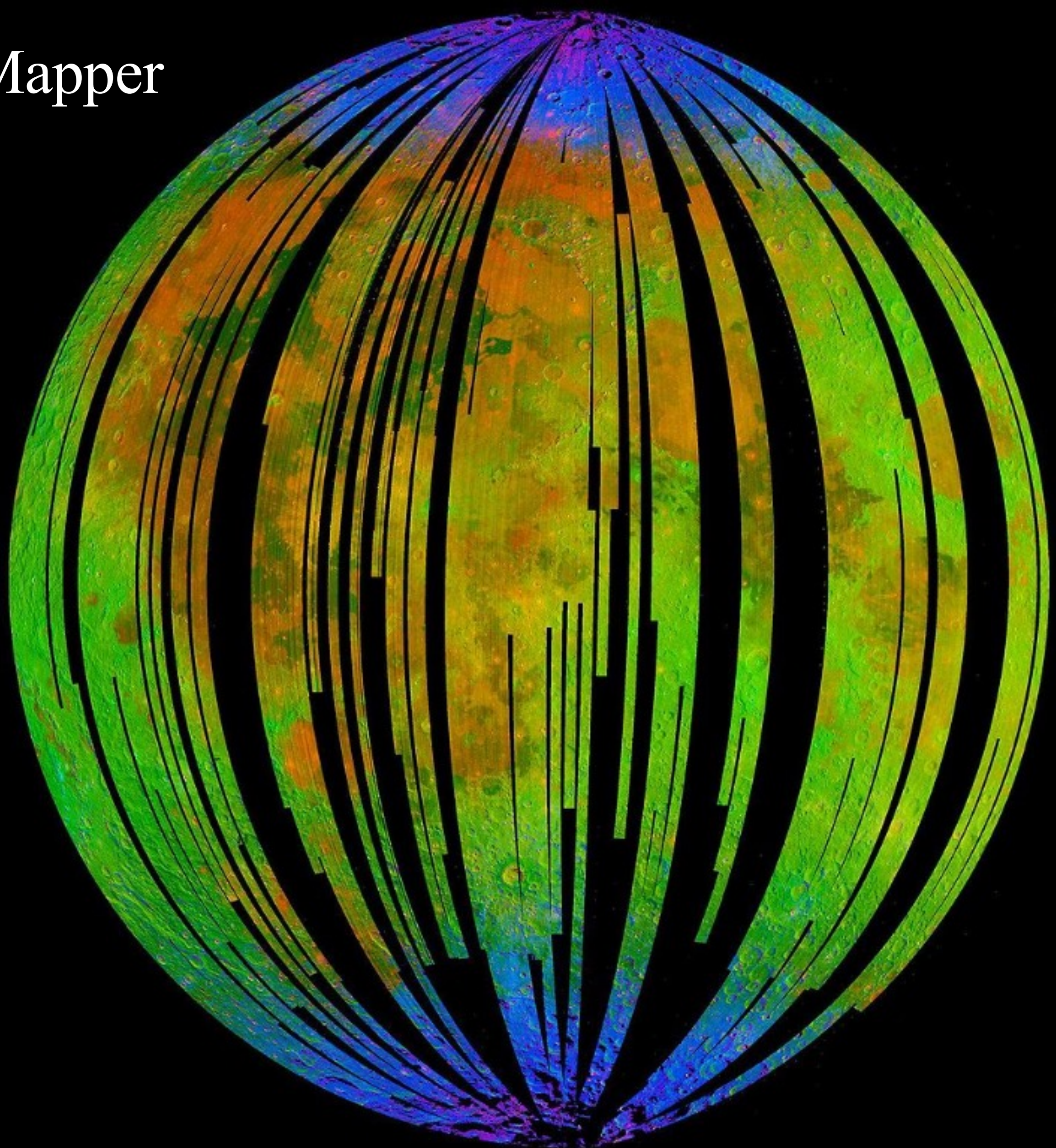
The Moon

- What are the characteristics of the Moon? How does the Moon compare to the Earth?
- What can its surface tell us about its history?
- How was the Moon formed?
- What use is the Moon?

Lunar Water

2008 Moon Mineralogy Mapper (India)
Blue = hydroxide (OH)
Green = IR
Red = pyroxene

2009 LCROSS
Impact on south pole + sampling
155 kg of water



Basic data

Average distance from Earth = 384,400km

Mass = 7.3 x 10^{22} kg = 1.2% M_{earth}

Diameter = 3476 km = ¼ Earth's

Density = 3344 kg/m^3

V_{esc} = 2.4 km/s

No atmosphere

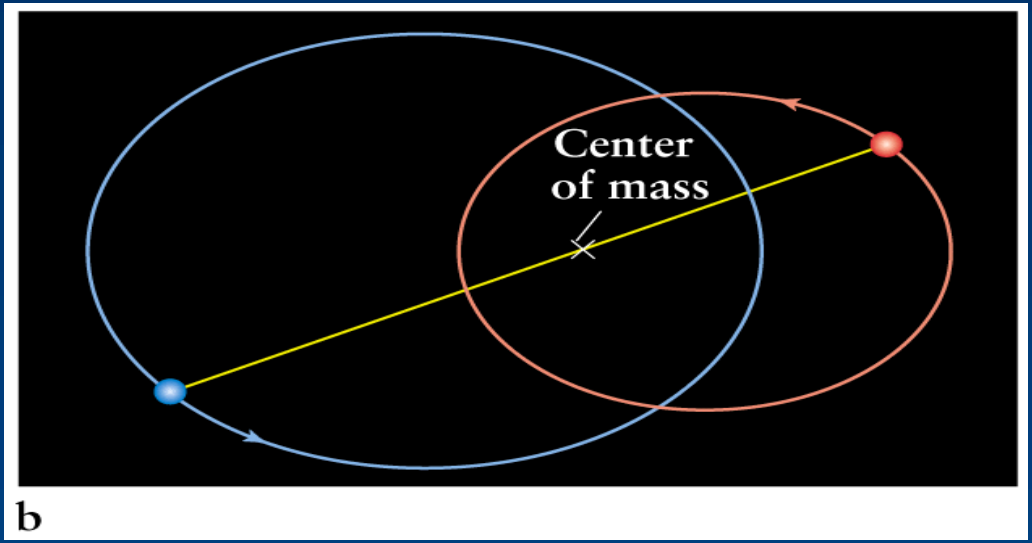
Albedo = 0.11

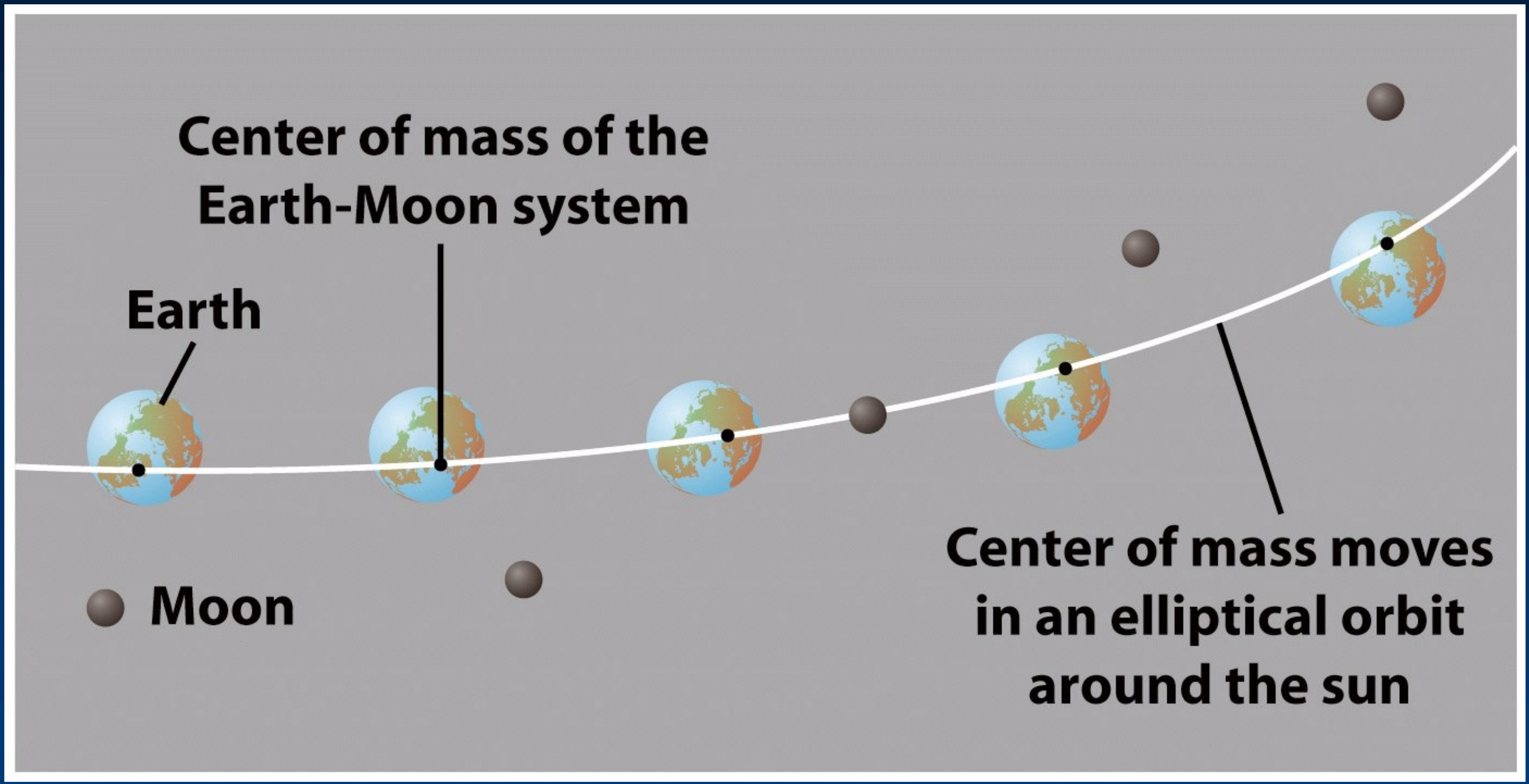
How do we measure the mass of the Moon?

Modern way: use $P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)}\right] a^3$ with an artificial satellite orbiting the Moon with known period.

Or, use the fact that the Moon and Earth orbit around center of mass (CM) of Moon/Earth system.

recall: $m_1 r_1 = m_2 r_2$, where r_1 and r_2 are distances to center of mass at any point in orbit





Earth wobbles around Earth-Moon center of mass – Earth does not exactly follow elliptical orbit around Sun. But center of mass does.

This wobble has period of 1 sidereal month (27.3 days) and can be measured with precise positions of stars and planets. Can determine center of wobbling motion, i.e. center of mass.

Result: average distance from Earth's center to center of mass is r_{Earth} = 4730 km in the direction of the Moon, i.e. still within the Earth. So average distance from Moon to center of mass is r_{Moon} = 384,400 km – 4730 km = 379,670 km. Hence:

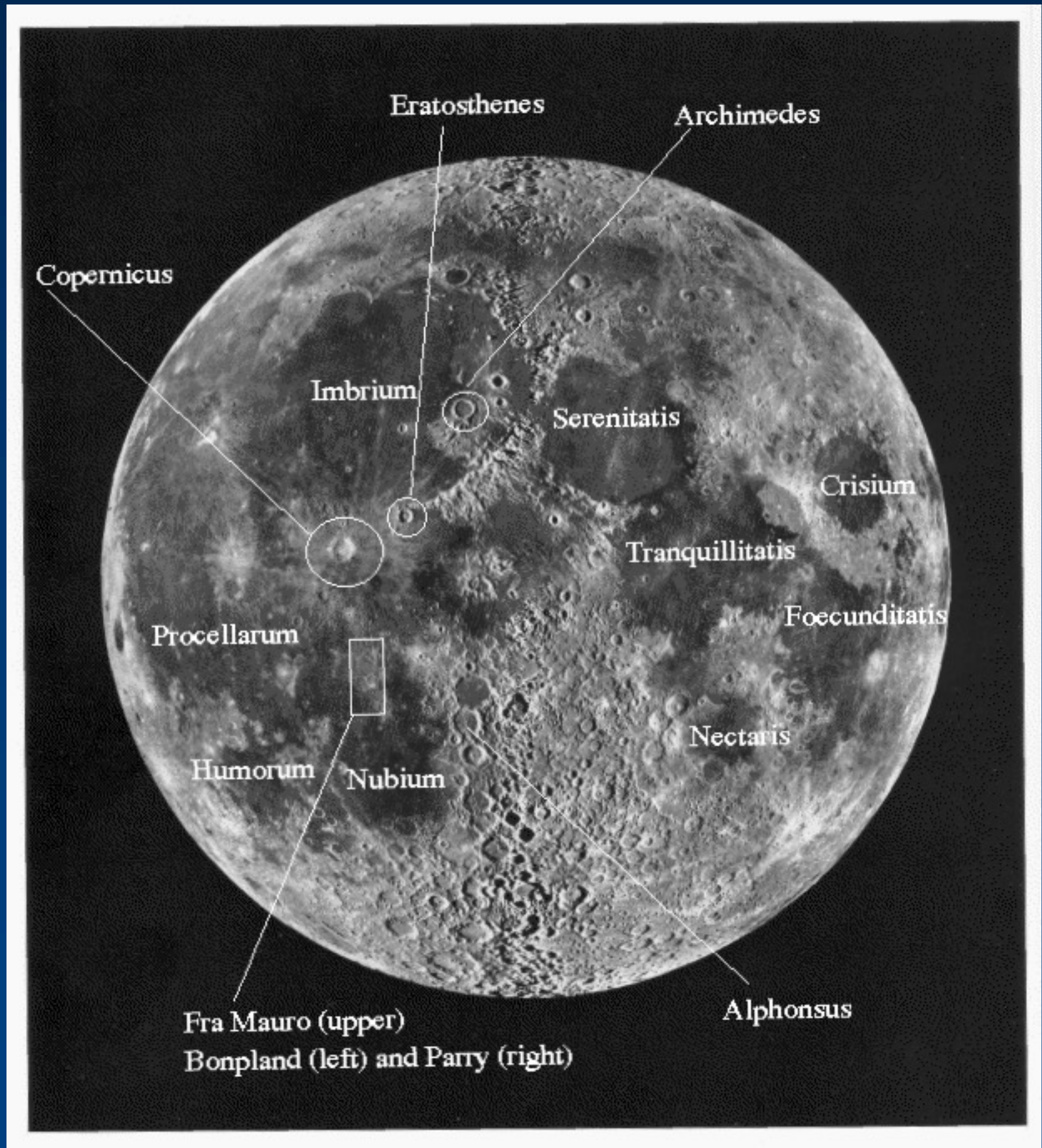
$$\frac{M_{moon}}{M_{Earth}} = \frac{r_{Earth}}{r_{moon}} = \frac{4730\ \text{km}}{379{,}670\ \text{km}} = 0.012$$

Then use a = 384,400 km and solve for total mass

$$P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)}\right] a^3$$

The surface of the Moon

- Near side has
  - *lunar highlands* (bright regions, mountains but no chains)
  - *marias* (dark regions) 2-5 km lower than highlands
  - Craters (surface density 10 times higher in highlands)
- If no water or wind erosion, the number of craters in an area tells you the age of the surface. Also no atmosphere in which small meteoroids burn up.



Age of surface?

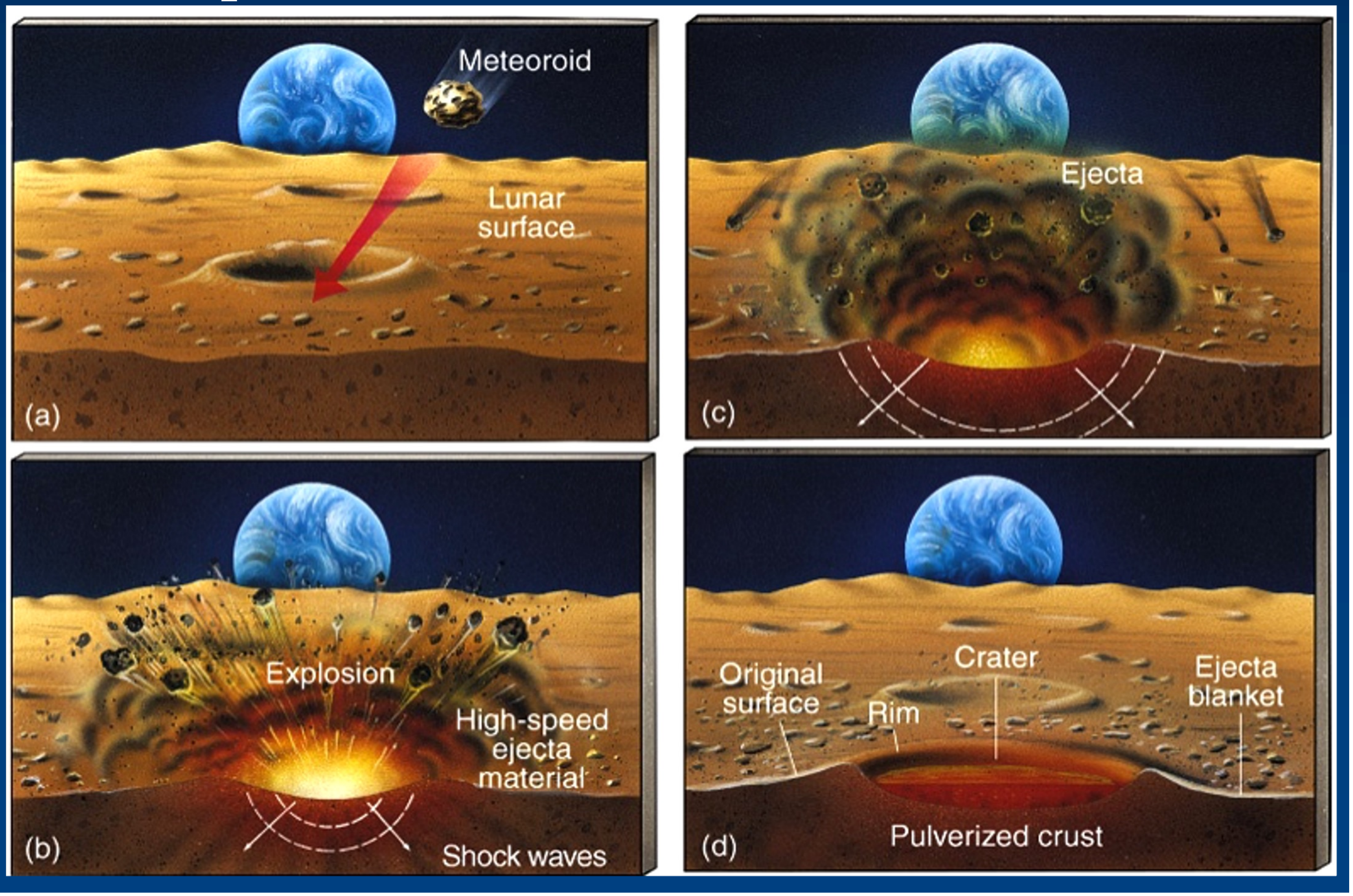
- More heavily cratered surface is older – so highlands older than maria

Comparison of Earth and Moon surfaces?

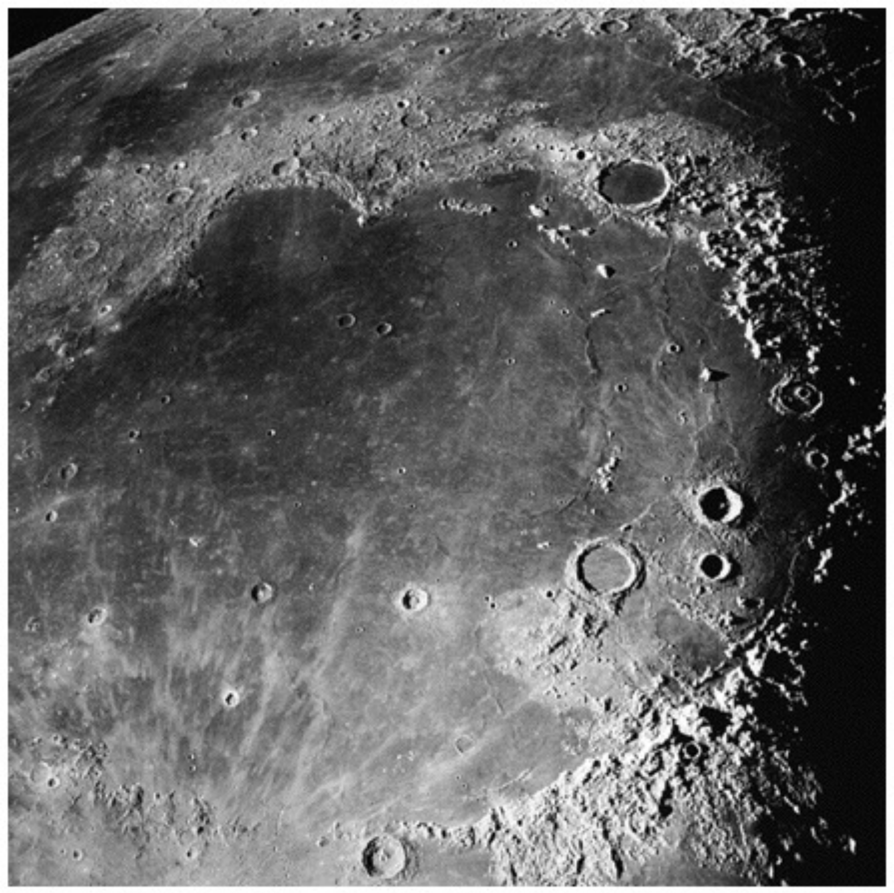
- Much higher crater density in general means surface of the Moon is older than that of the Earth, no geological activity for a long time (no plate tectonics, wind, or water erosion)

Also on the surface: regolith

- Regolith is a powdery soil with scattered rocks – 2 - 20 m thick layer. Craters are rich in heavy elements. Mining?
- Made from debris from impacts that create lunar craters
- Impact speeds several km/s
- Each crater is surrounded by an *ejecta blanket*

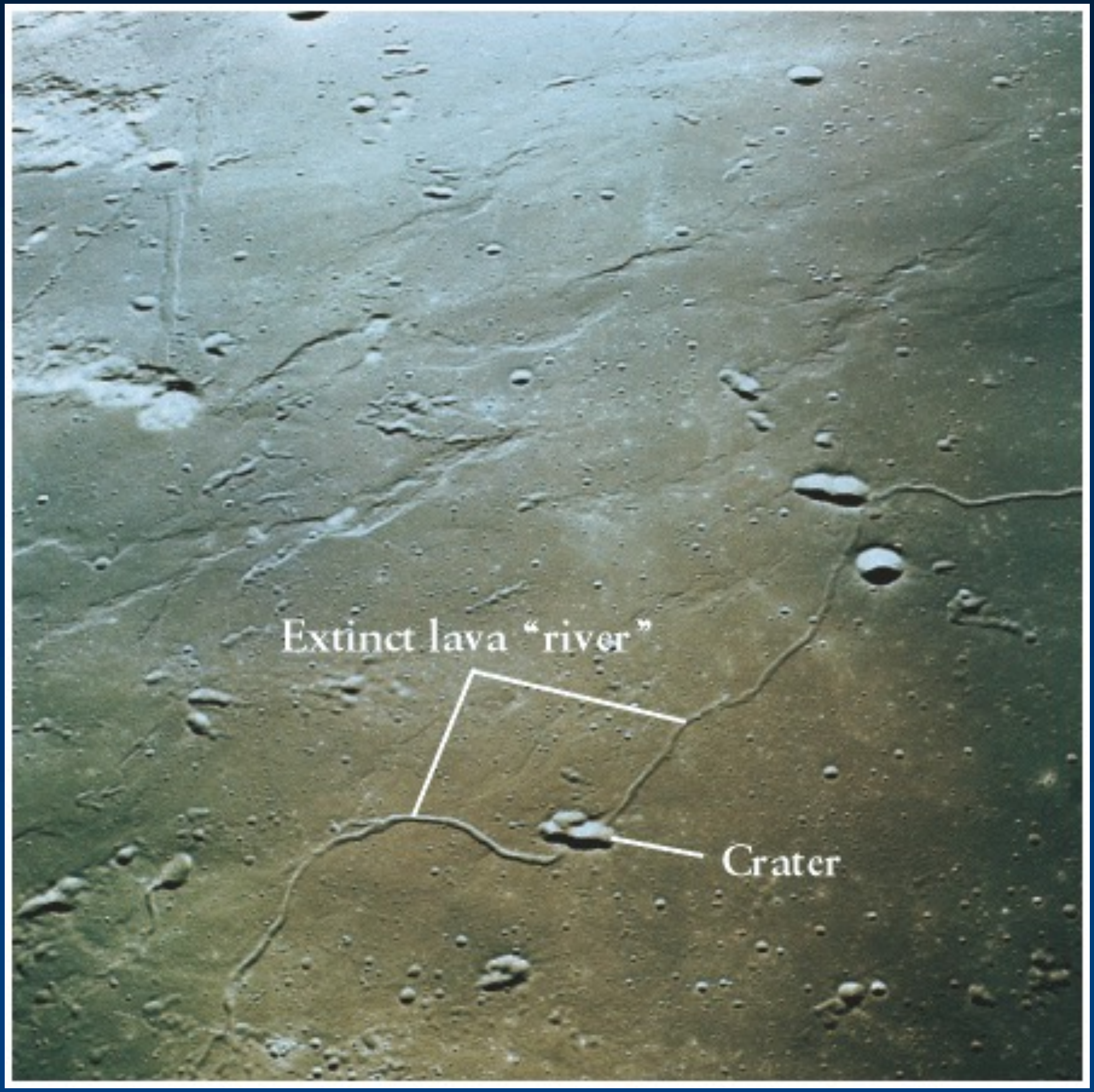


Evidence for past lava flows



Mare Imbrium – the largest of the maria facing Earth, about 1100 km across.

Maria are roughly circular – large early impacts
Also smooth and dark, like volcanic flows



This "river" was formed by lava, not water.

Moon rocks

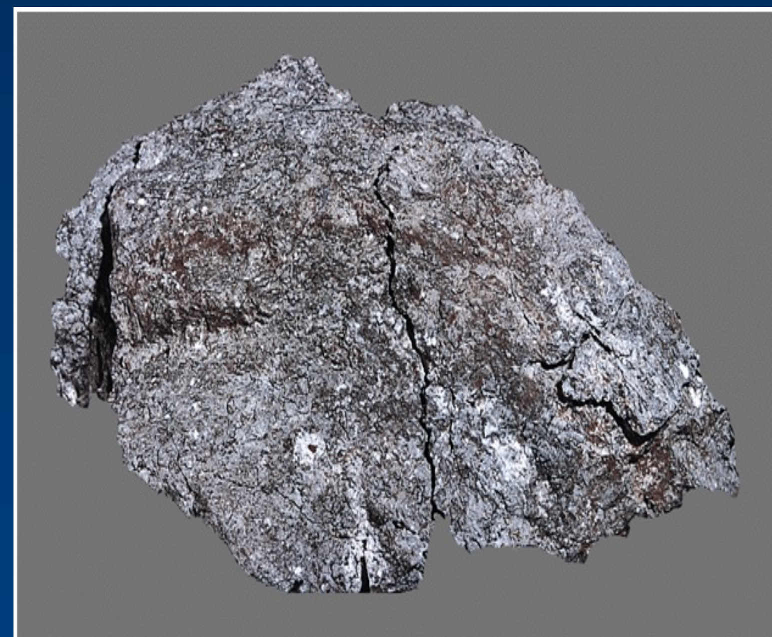
- 384 kg of rock samples from 10 missions:
- 6 Apollo landings [Apollo 11-17 (but not 13!) 1969-72]
- 12 astronauts visited maria and highlands
- 3 Soviet Luna robotic missions (1970, 72, and 76), returned rock samples by capsule
- … 44 year gap …
- Chinese mission in 2020 landed on the far side and returned 1.7 kg of lunar material to Earth

All returned samples are igneous ⇒ surface was molten.

Maria – basalts: Similar to rocks formed by lava on Earth

Highlands – anorthosites: Less dense than basalt

– breccias: Different rocks fused together in meteoritic impacts (also in marias)



Rocks also have no trapped CO_2, H_2O vapor like Earth rocks.

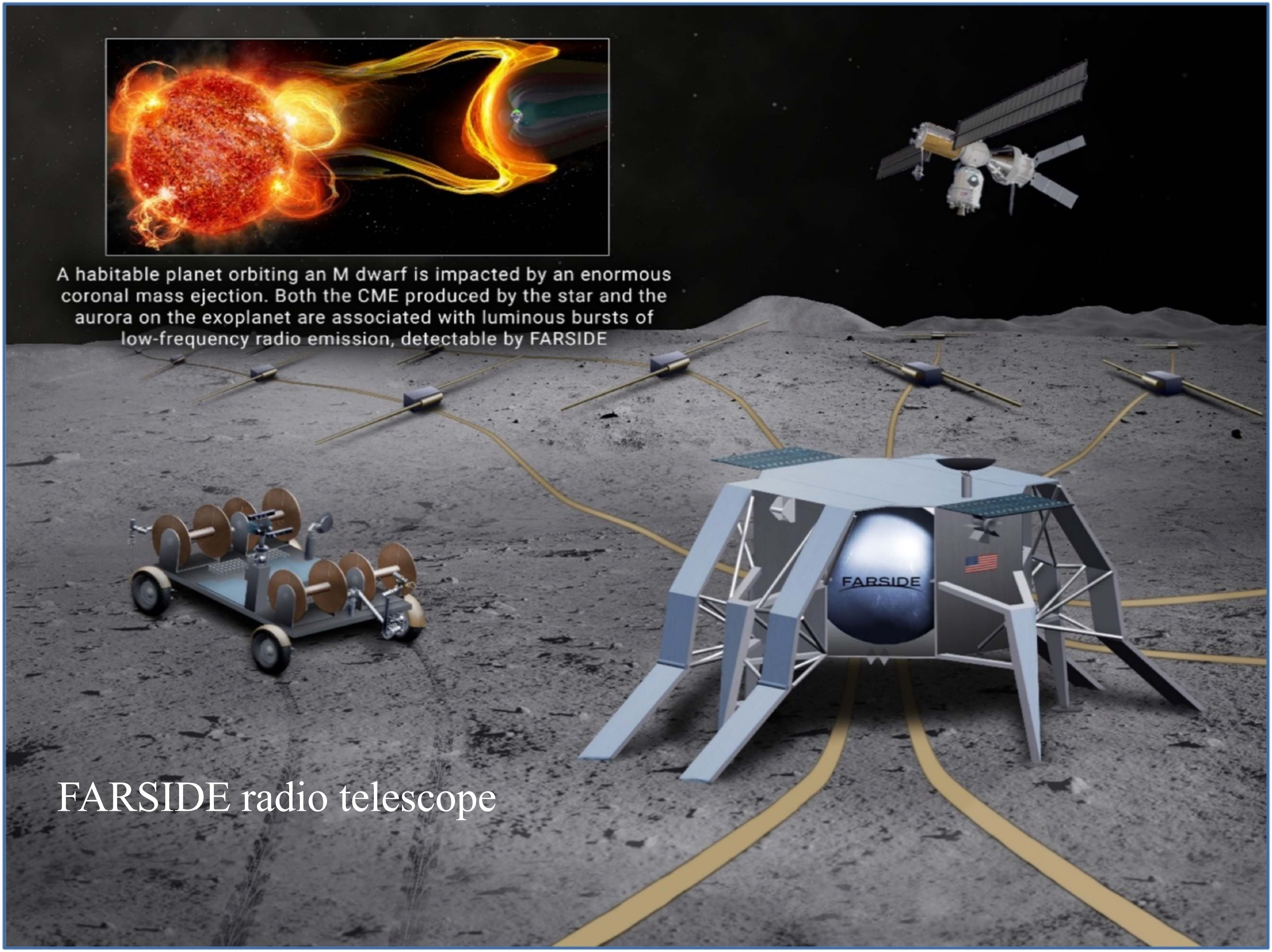
Lunar Surface

- Rocks rich in refractory elements (Ca, Al, Ti that forms compounds, high melting points)
- Poor in light elements like H, though there is ^{3}He from solar wind
- H_2O in polar regions

Mining on the Moon?

Interlune Co.


ARTEMIS
HUMANITY'S RETURN
TO THE MOON


A habitable planet orbiting an M dwarf is impacted by an enormous coronal mass ejection. Both the CME produced by the star and the aurora on the exoplanet are associated with luminous bursts of low-frequency radio emission, detectable by FARSIDE
FARSIDE
FARSIDE radio telescope

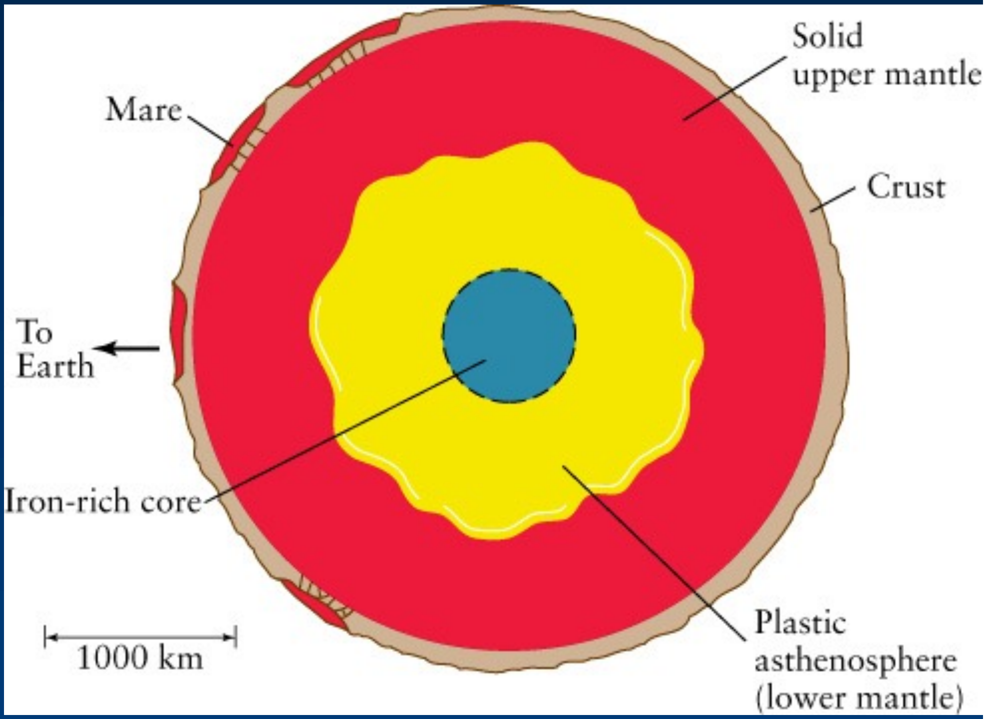
Age of Lunar material

- Radioactive dating can give more accurate ages than crater rates.
- Samples from Mare 3.1 – 3.8 billion years old
- Highland rocks typically 4-4.3 billion years, oldest rock dated to 4.46 billion years (oldest on Earth is 4.37 billion years)

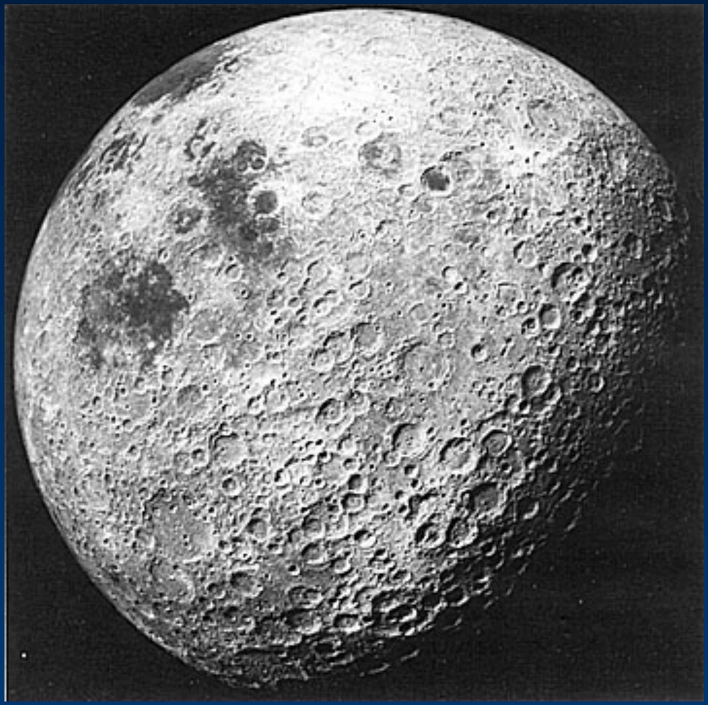
Oldest material on the Moon is almost as old as we believe the Solar System to be.

Moon's interior

- Astronauts left seismometers – moonquakes weak but useful



- Much thicker lithosphere than Earth, 800 km
- Relatively small iron-rich core, 700 km diameter. Only 2-3% of mass (32% on Earth). Moon differentiated, like Earth. Must have been molten.
- Thicker crust than Earth, 60-100 km – thicker on far side



Crust on far side is much thicker. Volcanic material could not reach surface. Reason seems to be that entire dense interior sags a bit towards Earth in a kind of differentiation due to Earth's gravity.

Geological history

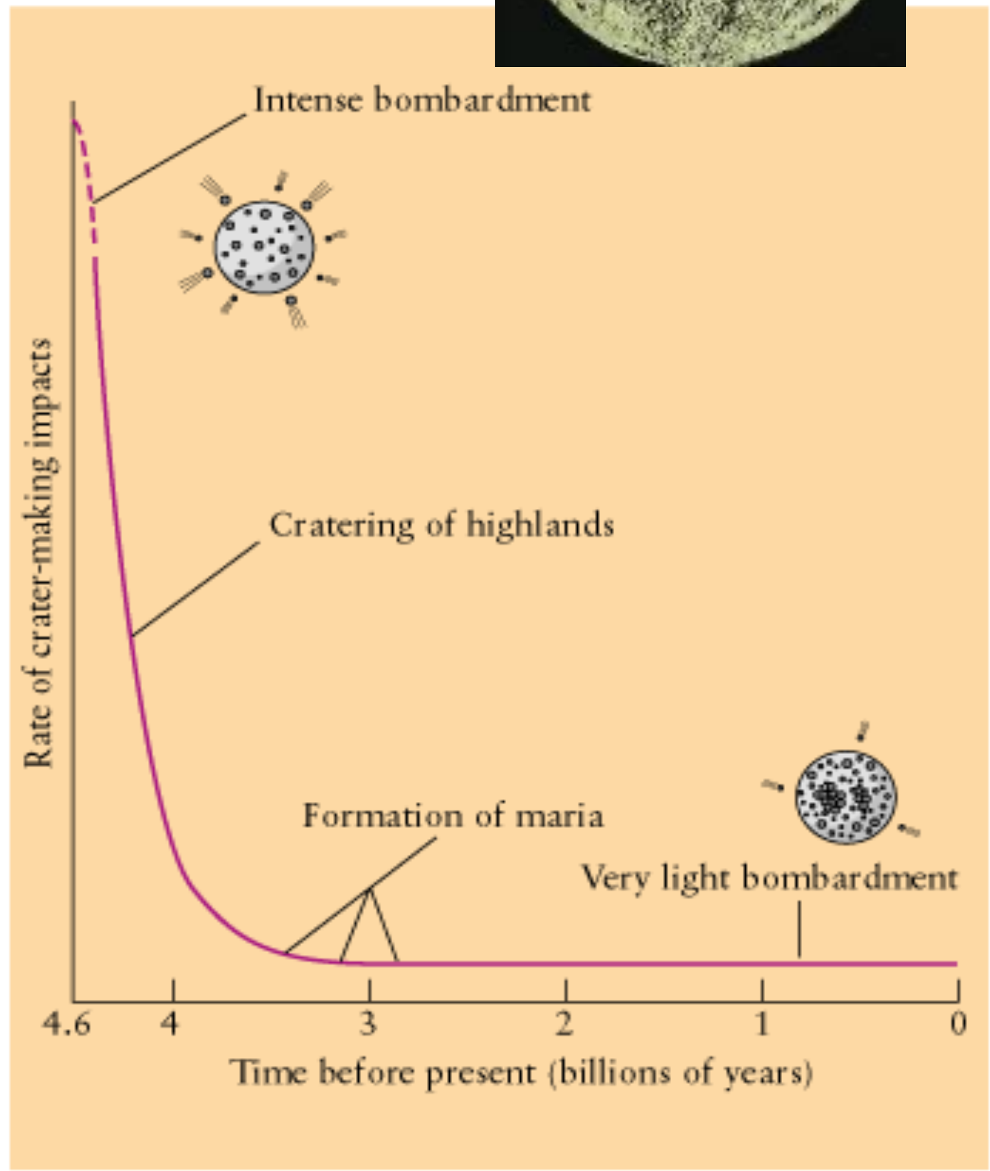
1. Formed 4.5 Gyrs ago. How? We'll come back to that.

2. Age 100 Myr: top few 100 km molten, from bombardment heat and short-lived radioactive elements. Solidified, and crust formed.

3. Heaviest bombardment ended after 1.7 Gyr: highland craters and large basins formed.

4. Age 1.7 – 2.4 Gyr: Radioactive heating from longer lived elements led to intense volcanic activity, filling large basins to create maria.

5. Age 1.5 Gyr: volcanism largely stopped, Moon nearly geologically dead since then. No plate tectonics. Surface is one solid plate. Light bombardment



Moon is largely dead geologically. Why?

No convection currents moving plates around

⇒ Moon is solid, because it has cooled off ⇐

$$\text{Cooling time} = C \, \frac{\text{heat content}}{\text{rate of cooling}}$$

Where C is just a constant

Heat content scales linearly with Volume

Rate of cooling scales linearly with surface area

Worksheet 13

No convection currents moving plates around

$\Rightarrow$ Moon is solid, because it has cooled off $\Leftarrow$

Cooling time $\propto$ heat content $\div$ rate of cooling

$\propto$ volume $\div$ area

$\propto R^3 \div R^2$

$\propto R$

The smaller the world, the less internal heat it is likely to have retained, and the less geologic activity it will show on its surface.

Origin of the Moon

Any theory must explain:

- Moon has lower density than Earth, much less iron
- Moon lacks water and other volatiles (substances with low boiling temperatures like sodium, potassium, water, CO_2)
- Moon rocks lack iron and high density materials, different from Earth on average, but similar to mantle

How did the Moon form?

We're not quite sure! Three older theories:

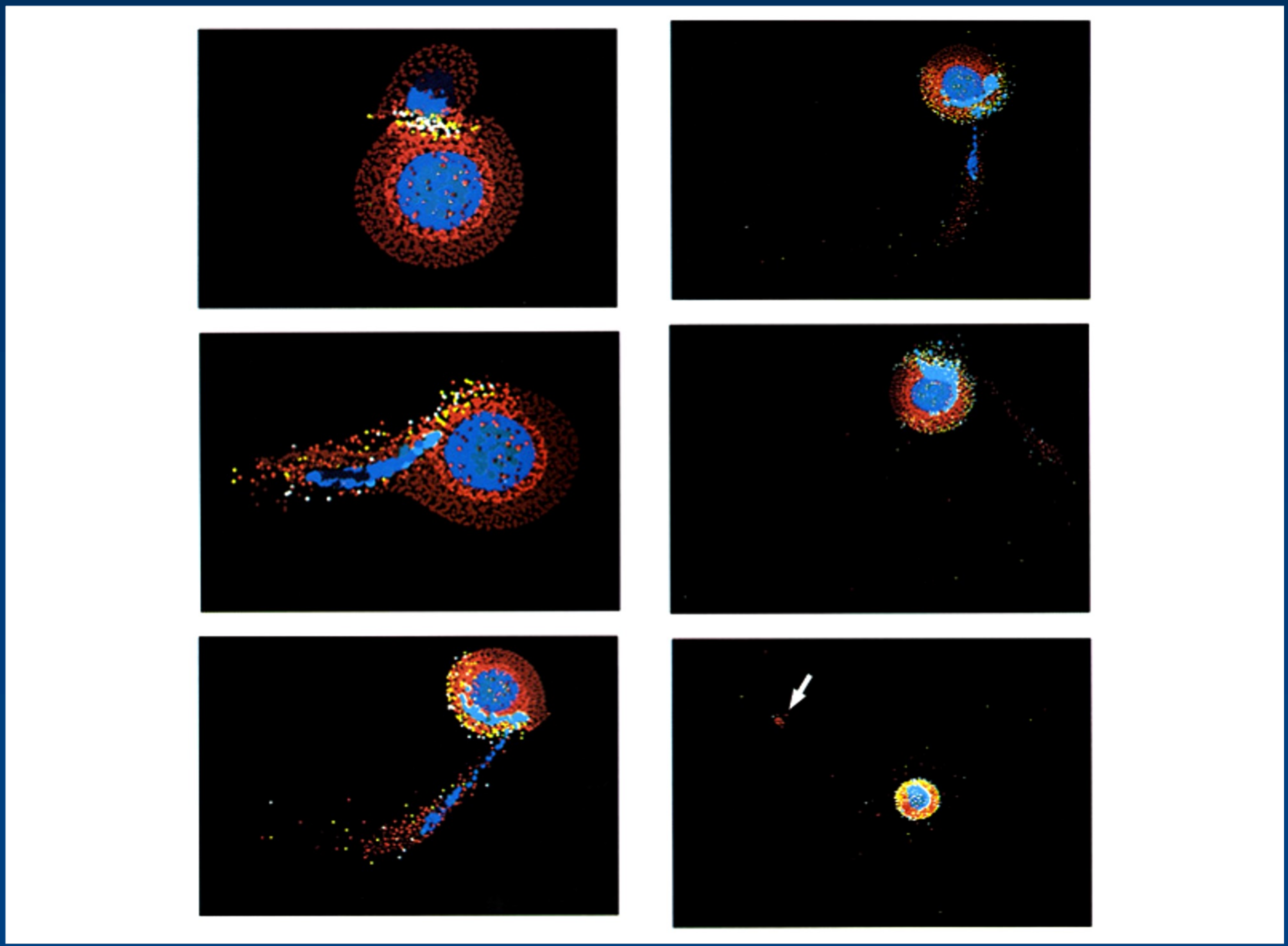
1) "Fission": The material that would be the Moon was thrown off the Earth and coalesced into a single body. Problem: Earth not spinning fast enough to eject large amount of material.

2) "Coformation": The Moon and Earth formed out of the same material at the beginning of the Solar System. Problem: Moon has different density and composition.

3) "Capture": The Moon was a stray body captured into orbit around Earth. Problem: an extremely unlikely event, given Moon's size is a substantial fraction of Earth's.

So now, Impact theory preferred:

Early in Solar System, when many large planetesimals around, a Mars-sized object hit the forming Earth, ejecting material from the upper mantle which went into orbit around Earth and coalesced to form Moon. Computer simulations suggest this is plausible.

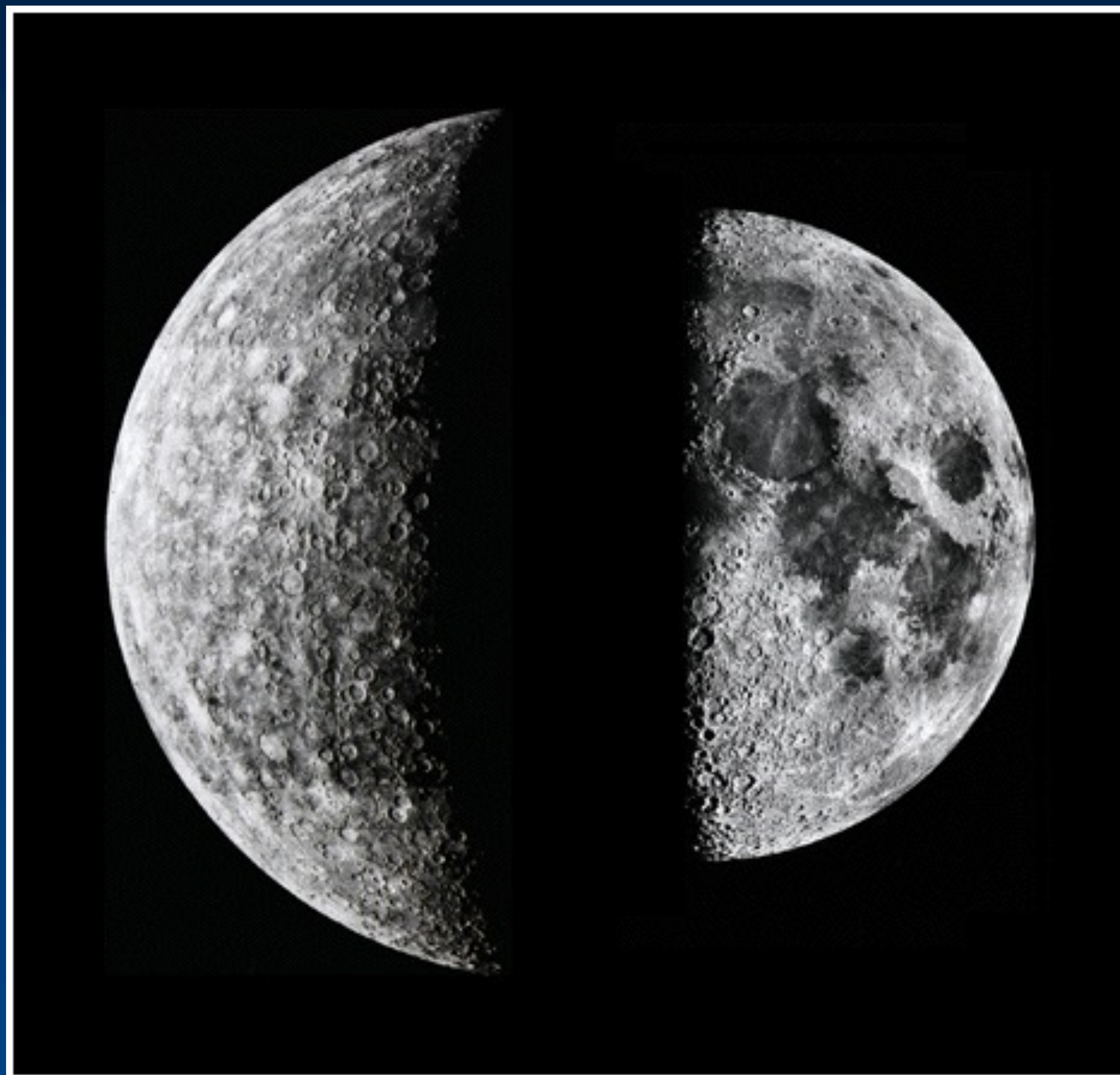


So now, Impact theory simulation:

https://www.dailymail.co.uk/sciencetech/article-9015061/Supercomputer-simulation-shows-Moon-formed.html

Some of the strong points

- Spectacular collisions must have happened at end of planet building. Few dozen large bodies that had been built collided to make the few planets we have (or were ejected)
- If Earth differentiated before time of collision, little iron near surface. Agrees with low density and iron content of Moon
- Moon formed of Earth's mantle debris => compositional similarities (oxygen isotope ratios)
- Lower abundances of volatile elements on Moon - rock vaporized by collision would have lost these elements



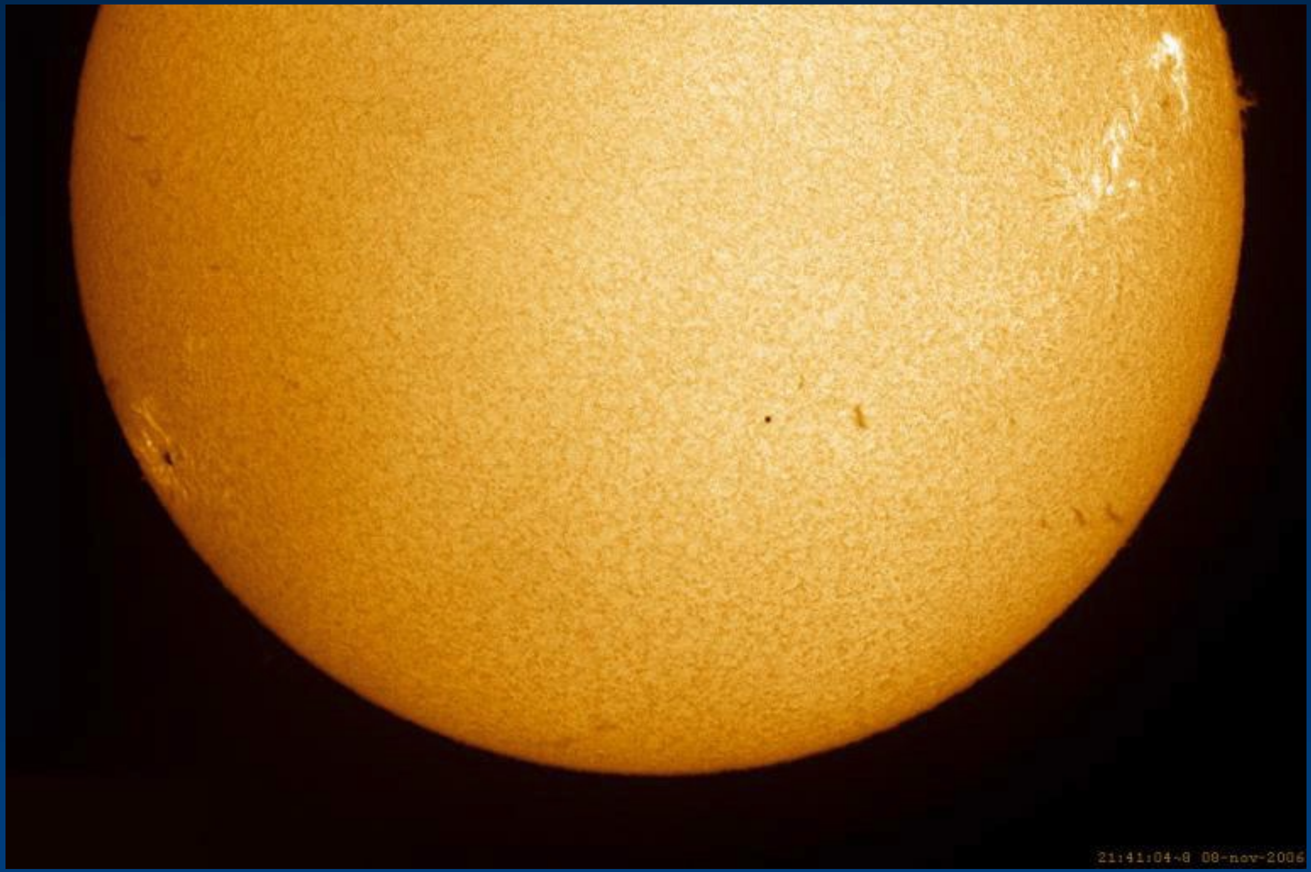
Mercury basic data

Semi-major axis	= 0.39 AU
Eccentricity	= 0.206
Inclination	= 7° (wrt ecliptic)
Orbital period	= 88 Earth days
Rotation period	= 59 Earth days (sidereal)
Diameter	= 4880 km = 0.38 Earth diameter
Mass	= 3.3×10^{23} kg = 5.5% Earth mass
Density	= 5430 kg/m^3 = 5.4 g/cm^3
V_{esc}	= 4.3 km/s
Temp	= 103 to 623 K
Albedo	= 0.12

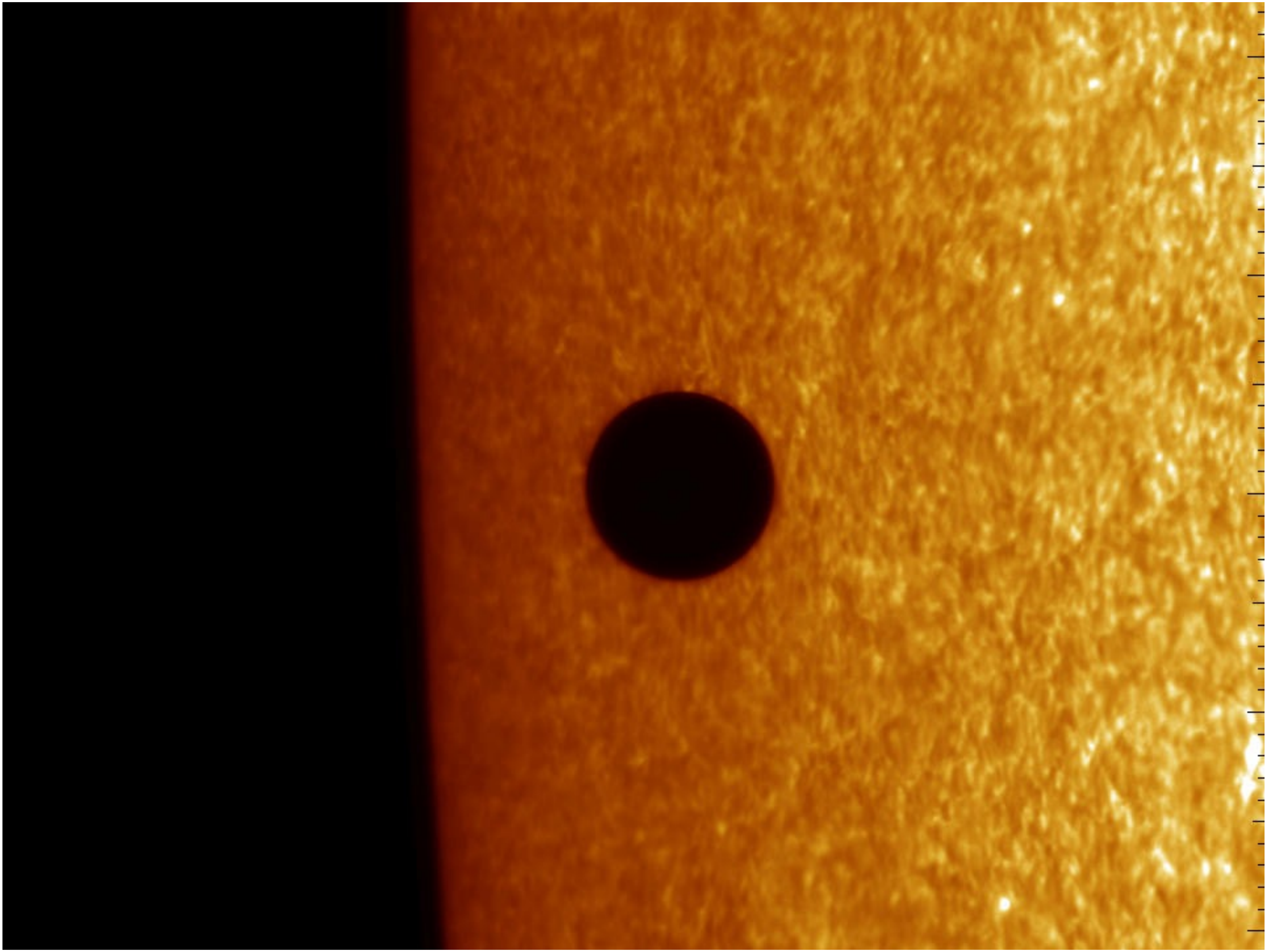
Appearance:

- Albedo 0.12.
- Hard to see since max elongation is only 28°
- Always too close to Sun for Hubble to observe
- Best ground-based telescope photos show little detail

Mercury transit in 2006

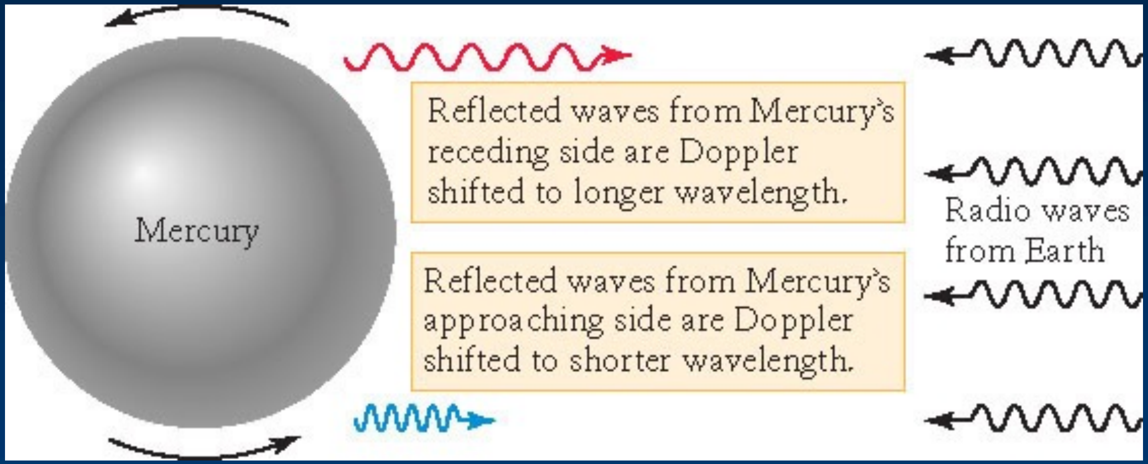


Transits do not occur every year, but only ~14 times a century, due to the 7° inclination of Mercury's orbit to the ecliptic. Next transit Nov 13, 2032.

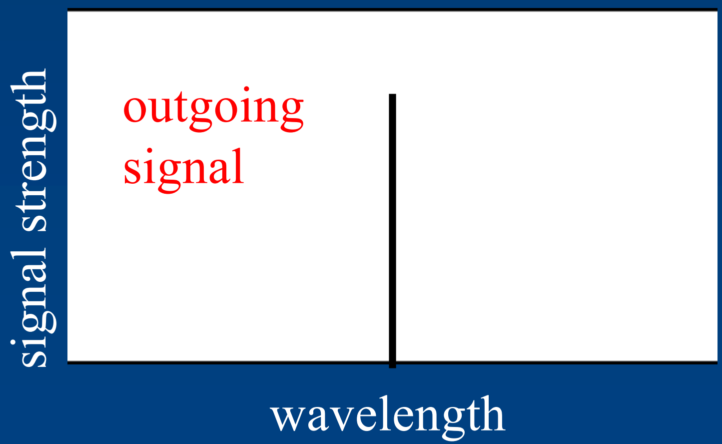


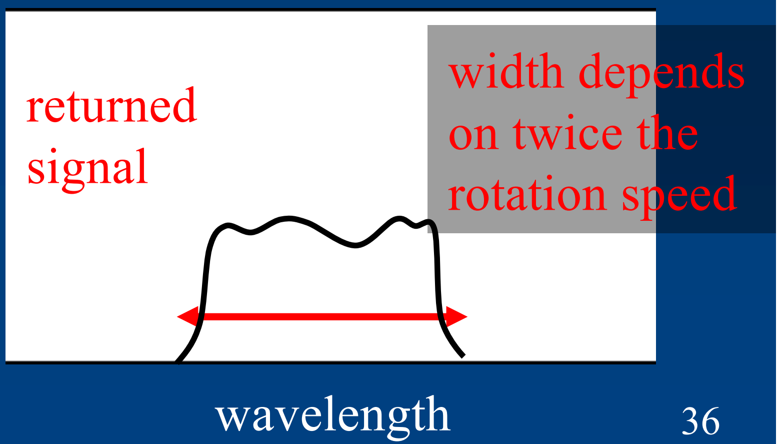
Mercury's orbit and rotation

How do we measure rotation of a planet?



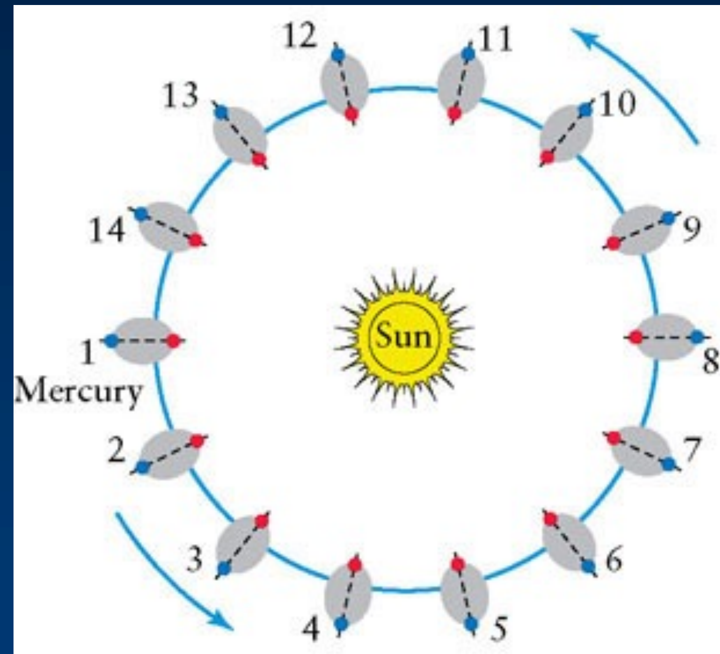
Even if angular resolution not high enough to resolve approaching and receding hemispheres, the returned signal will still have a width in frequency due to the outgoing signal bouncing off both hemispheres.



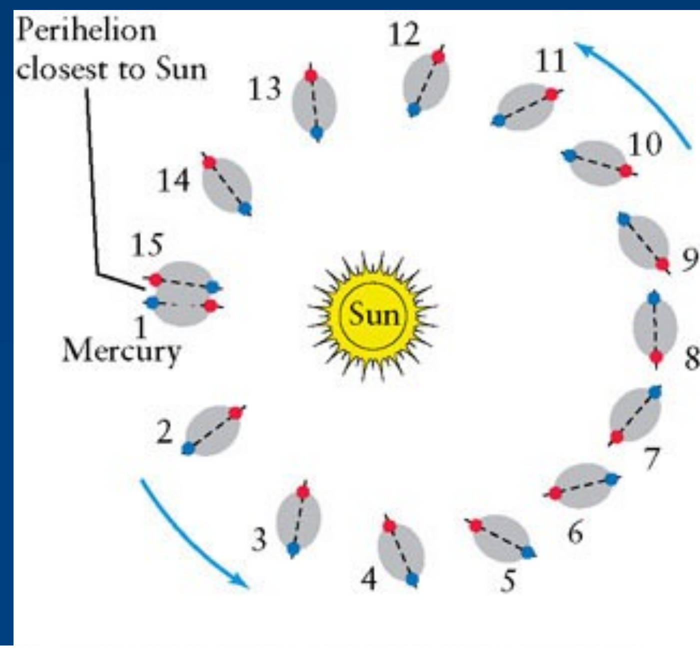


Mercury's orbit and rotation

Mercury has a tidal bulge due to Sun. If Mercury had a circular orbit, it would be in a 1:1 spin-orbit coupling (synchronous rotation).



But because of high eccentricity, can't be tidally locked over orbit. Tidal force so much stronger at perihelion, ended up being tidally locked there only. Rotation period = 2/3 of orbital period.

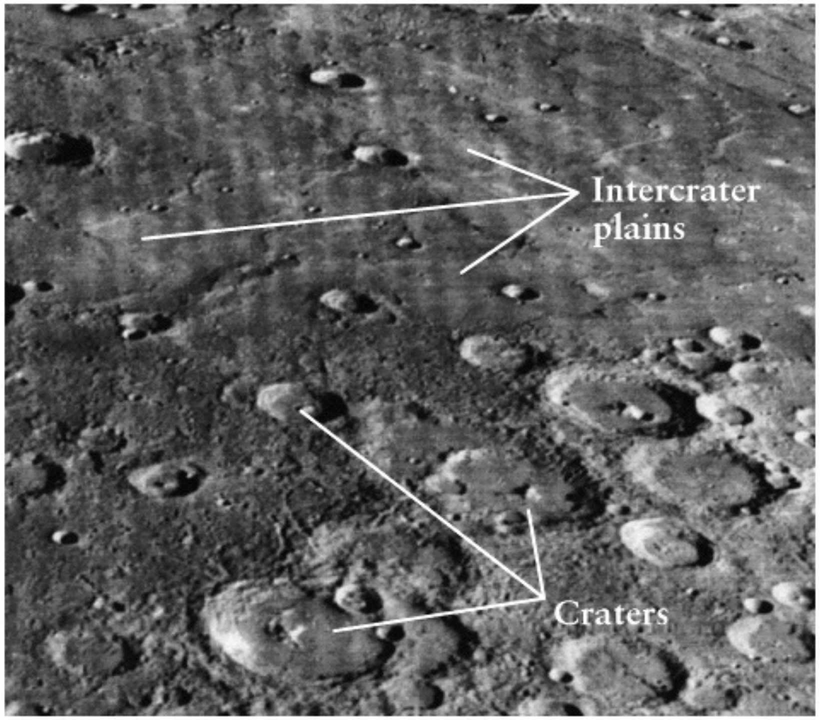


Orbital period = 3/2 rotation period exactly, so alternating ends of bulge always line up at perihelion. A "3:2" resonance orbit.

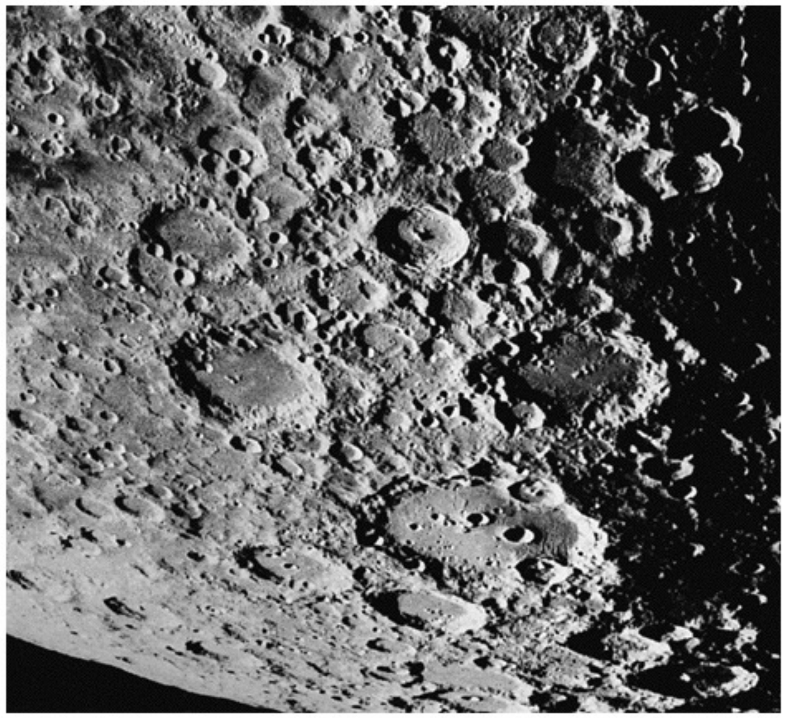
Spacecraft missions

- Previous mission: US Mariner 10 flew past Mercury 3 times in '74 & '75.
- About half of surface was imaged (sunlight direction)

Mariner 10 (1974 – 75): looks similar to far side of Moon: Mercury has craters, mountains, plains, impact basins (small versions of maria).

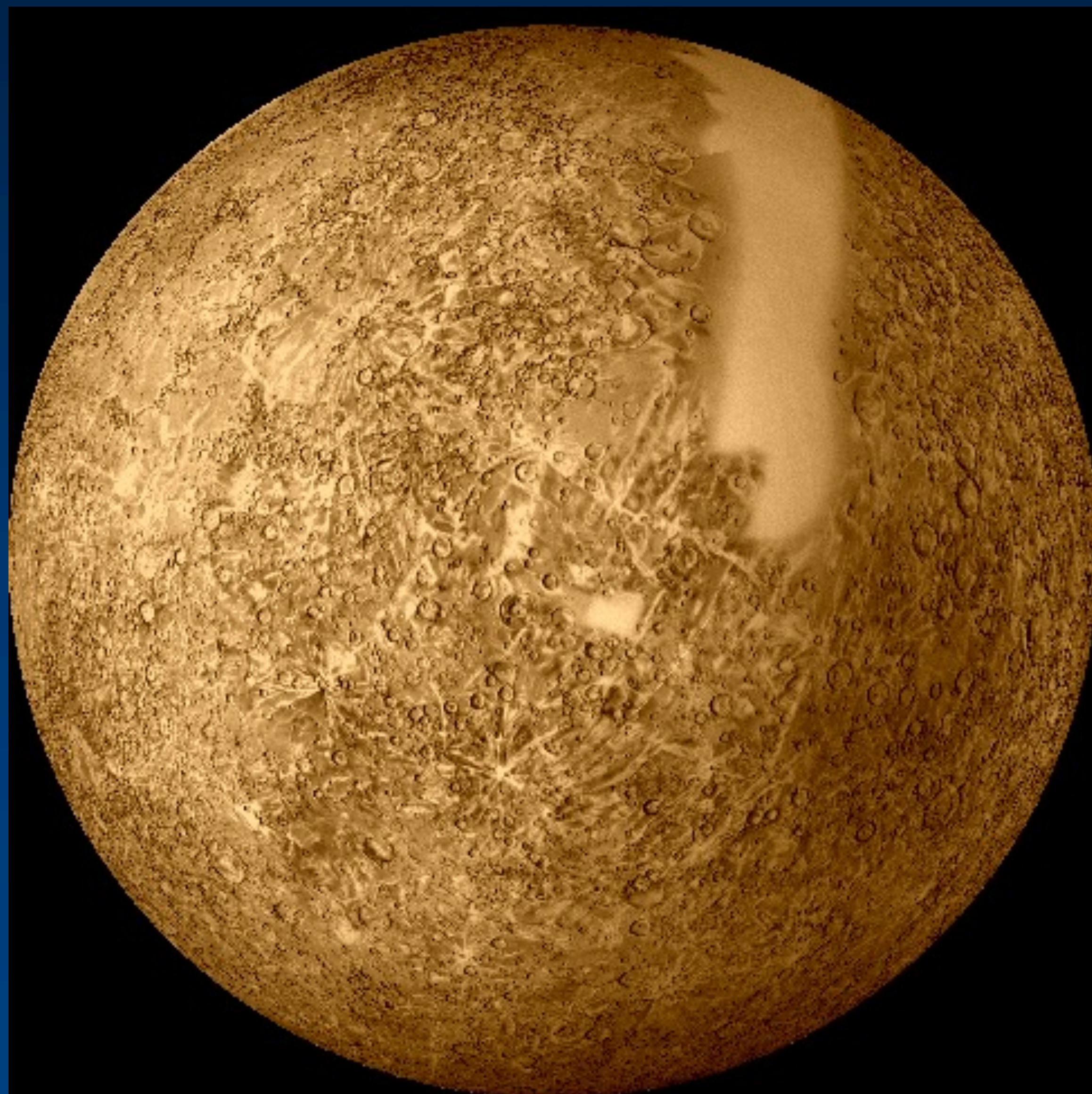


Mercury



Far side of Moon

Mercury's surface

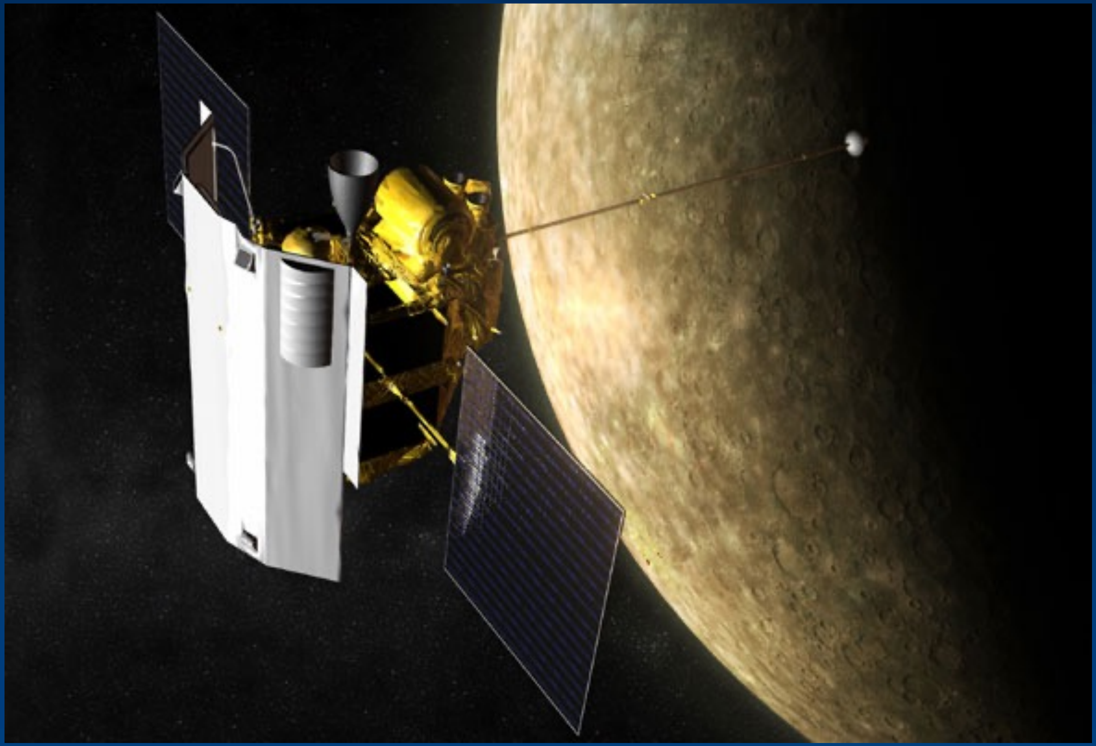


Mariner 10 mosaic – 1 km resolution

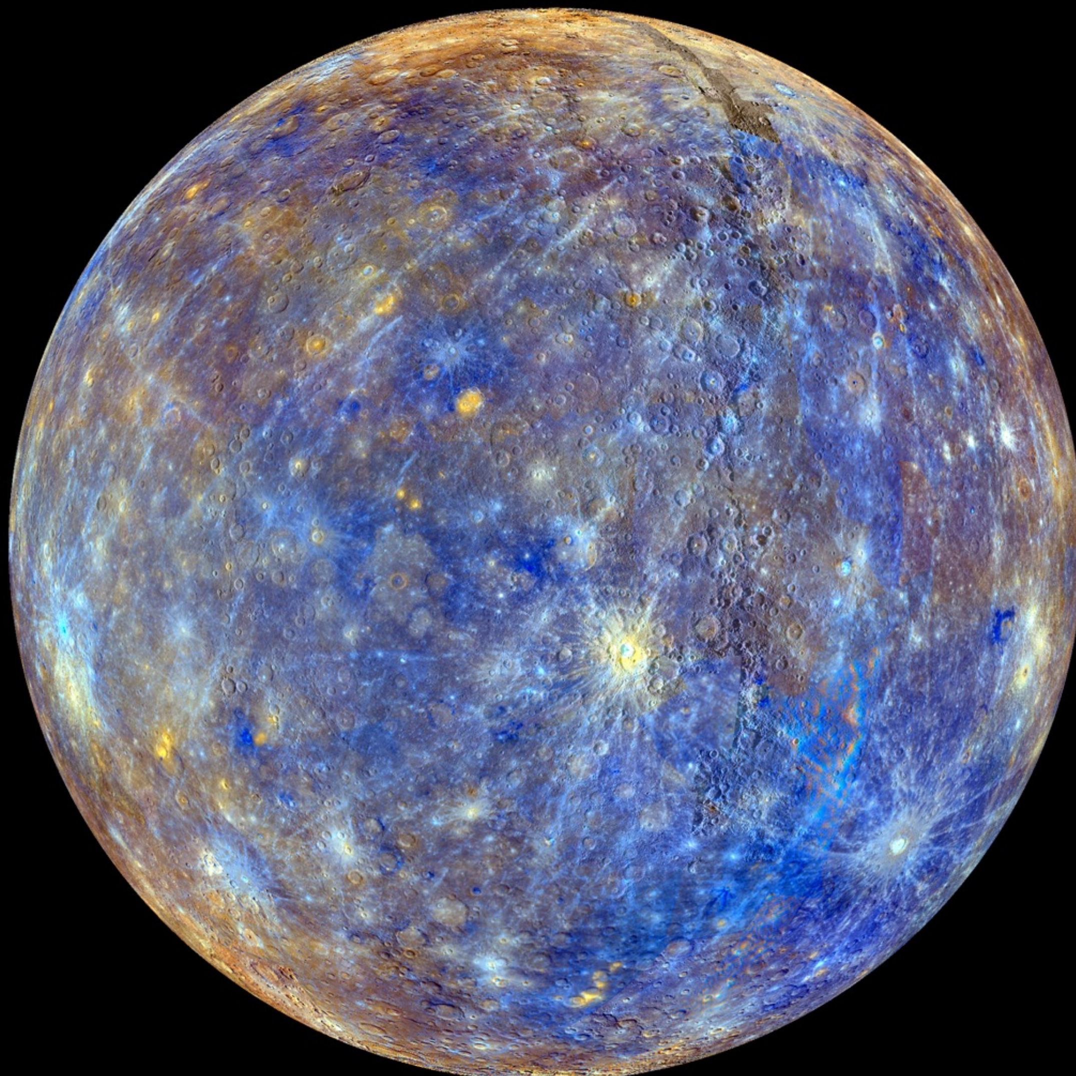
Recent mission

- NASA spacecraft MESSENGER (*MErcury Surface, Space ENvironment, GEochemistry, and Ranging)* launched in Aug. 2004.

- Fly-bys: Earth 04
  Venus 06, 07
  (gravity assistance)
  Mercury 3 times in 08, 09
  to map entire surface
  and 2011 entered orbit.



Mercury's surface

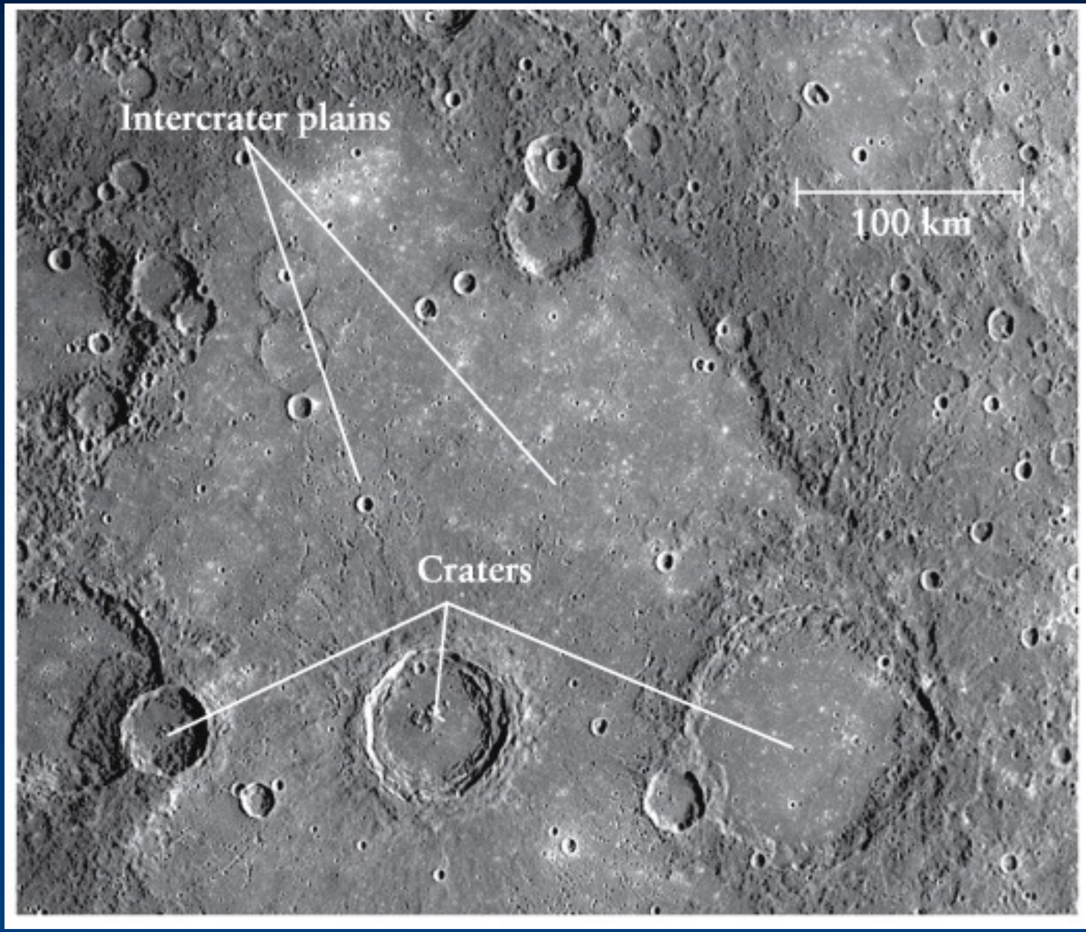


MESSENGER has imaged about 99% of surface, at 250-m resolution.

Mercury's surface compared to Moon

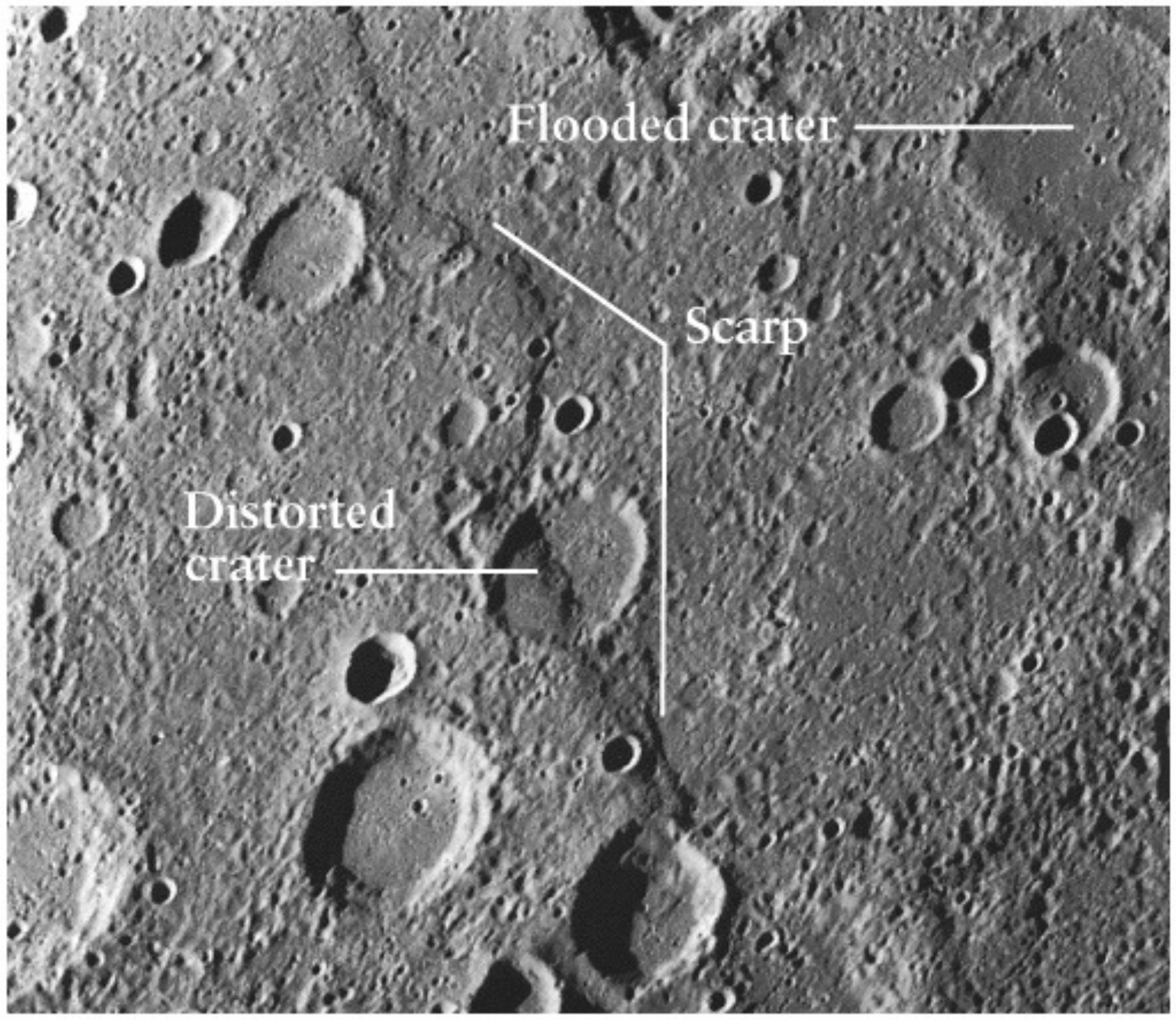
- No significant atmosphere (like the Moon) [but tenuous (pressure $<10^{-12}$ that of Earth's) *exosphere* of gas generated and maintained by the interaction of the solar wind with the planet's surface and magnetic field]
- Heavily cratered (like the Moon)
- 3.8 - 4 Gyrs old (similar to lunar highlands)
- No plate tectonics, water or wind erosion (like the Moon)
- Surface well preserved (like the Moon)

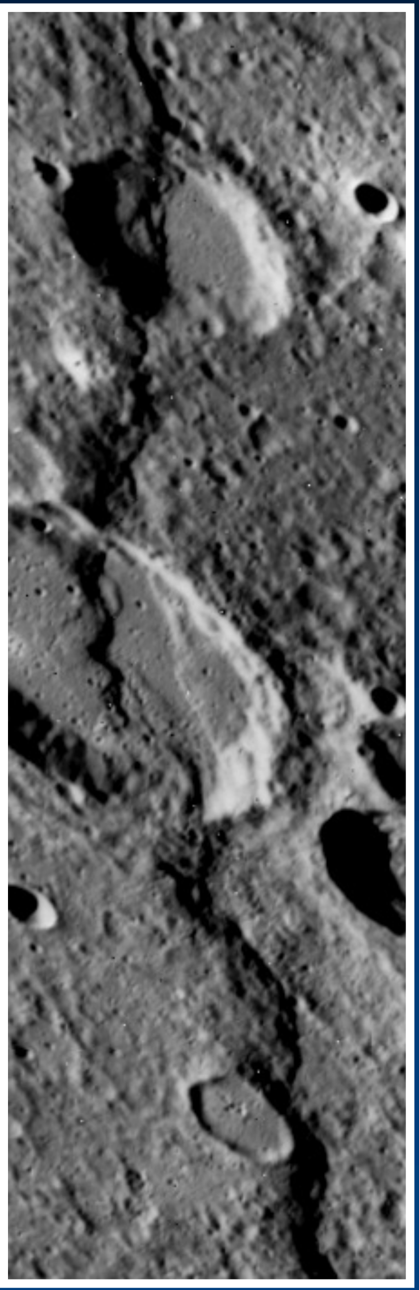
- "Intercrater plains" are 2 km lower than cratered terrain. Probably old lava flows - cratering rate indicates age of 3.8 Gyr.

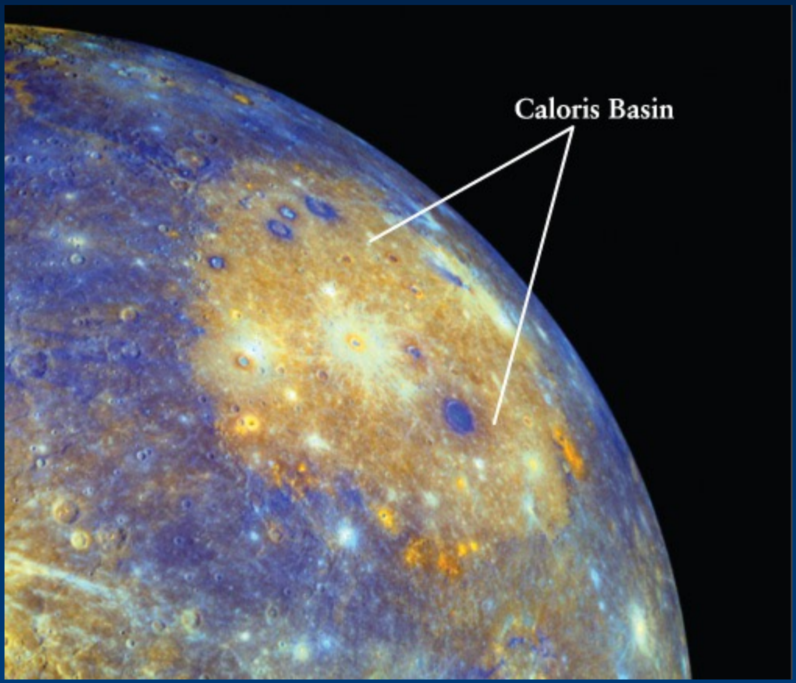


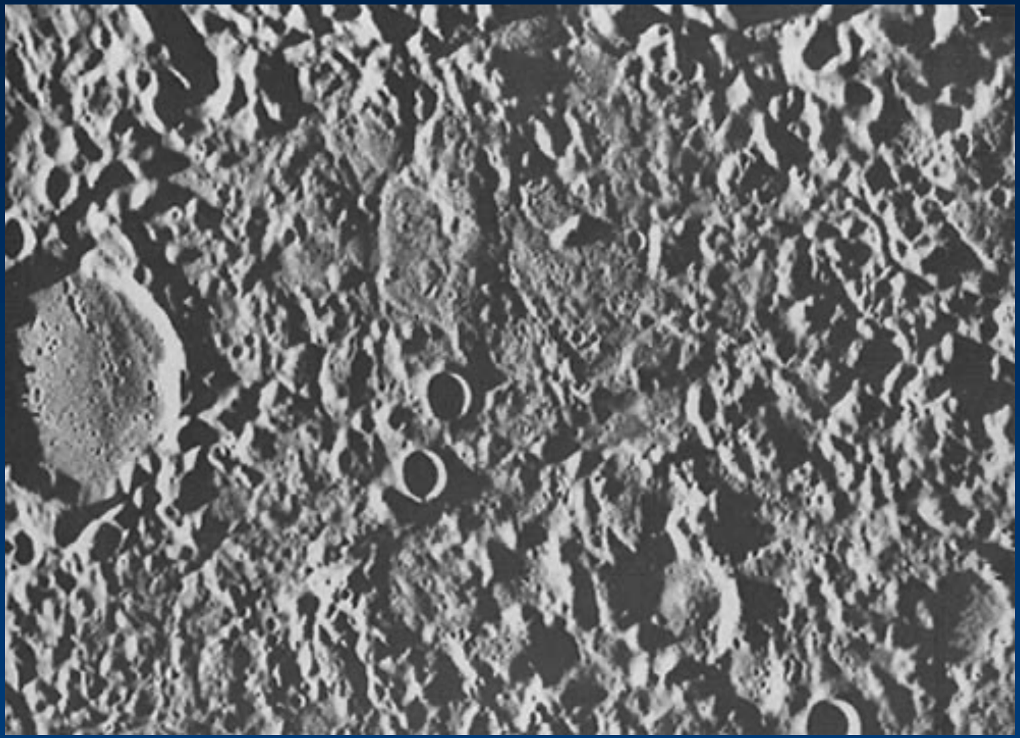
MESSENGER image

One unique feature: scarps. These are long cliffs, though to be caused by a cooling, contracting planet.





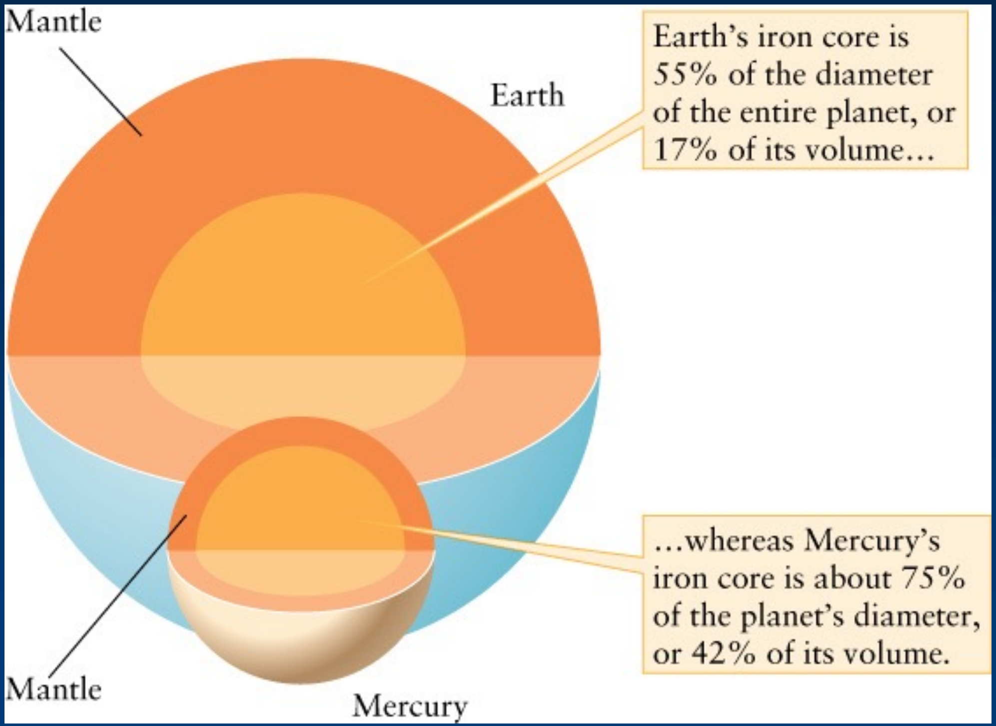




Caloris Basin – from large impact, about 3.9 Gyr ago. Created rings of mountain ranges (color heavily enhanced)

Created "jumbled" terrain on opposite side (due to convergence of seismic waves).

Structure of Mercury



- Denser than expected if just a smaller version of Earth (Earth' s slightly higher density due to compression by higher gravity).
- Hence, relatively large iron core (most iron-rich planet).
- Possibly only iron-rich materials could be solid so close to forming Sun. Or solar wind removal of mantle? Or big impact?

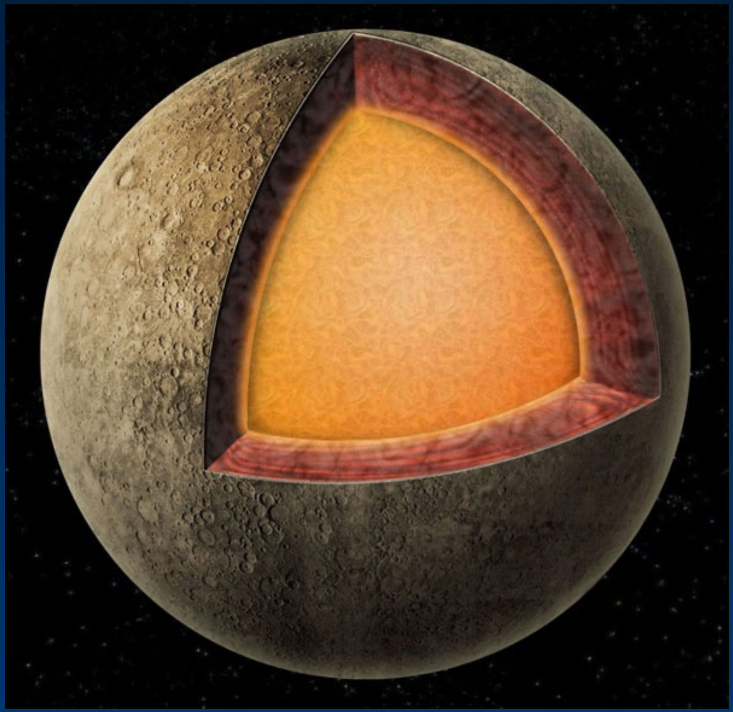
Is the core liquid or solid?

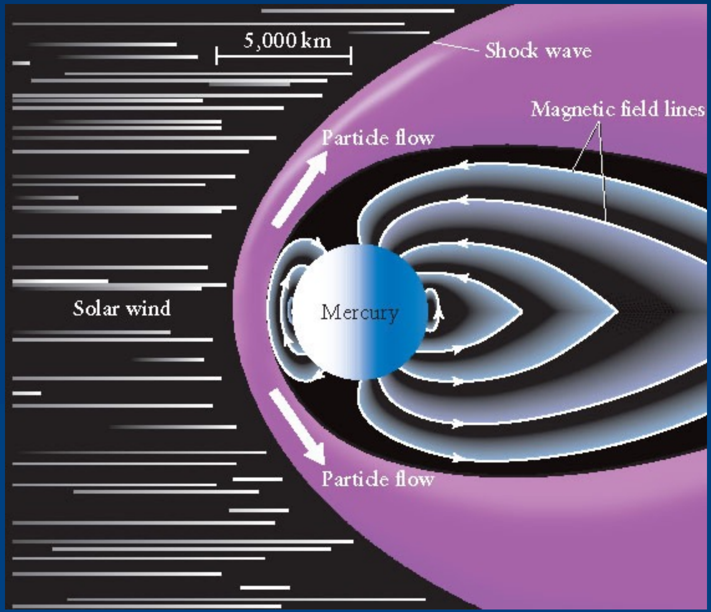
Mercury is small, should have solidified by now

However, has a magnetic field (1% of Earth's)

Liquid vs. solid would depend on composition

Recent MESSENGER result: magnetic field offset to the north of the center of the planet, by 20% of planet's radius. Not understood!





Evolution of Moon and Mercury

- Small masses

  ⇒ low escape velocities, thus no atmospheres retained.

- Small bodies

  ⇒ cool off quickly, thus no plate tectonics, or strong magnetic field.

- No erosion of surface or crustal evolution

  ⇒ retain “old” features.

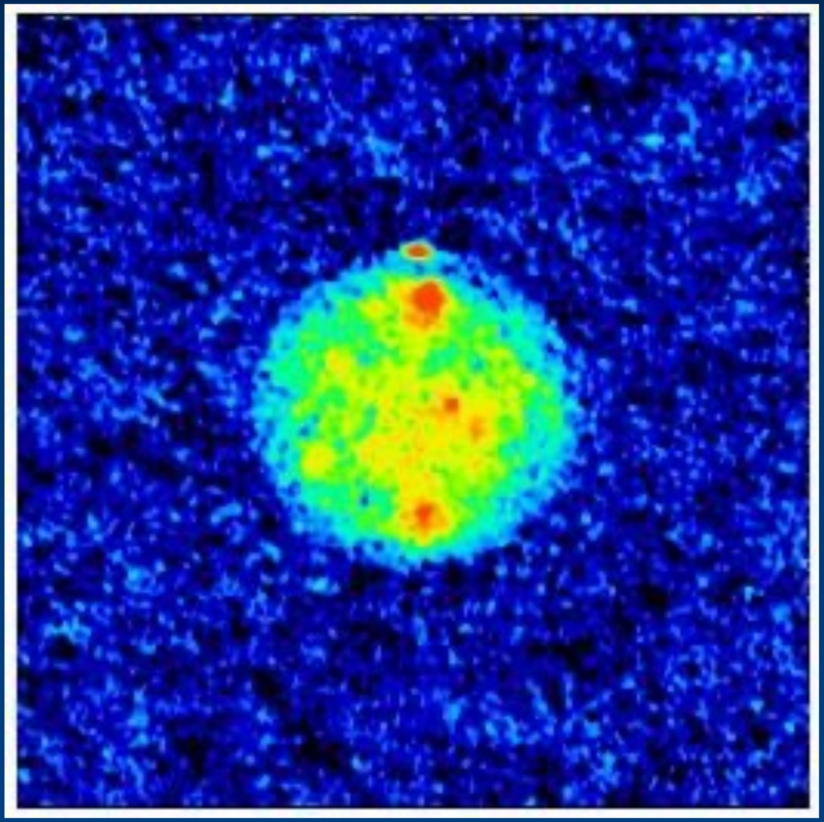
Ice on Mercury???

- No significant atmosphere => large day and night time temperature variations (103 – 623 K)
- Also, long days and nights increase temperature differences
- Very little tilt of rotation axis => poles in constant twilight
- Polar surface cold, 125 K

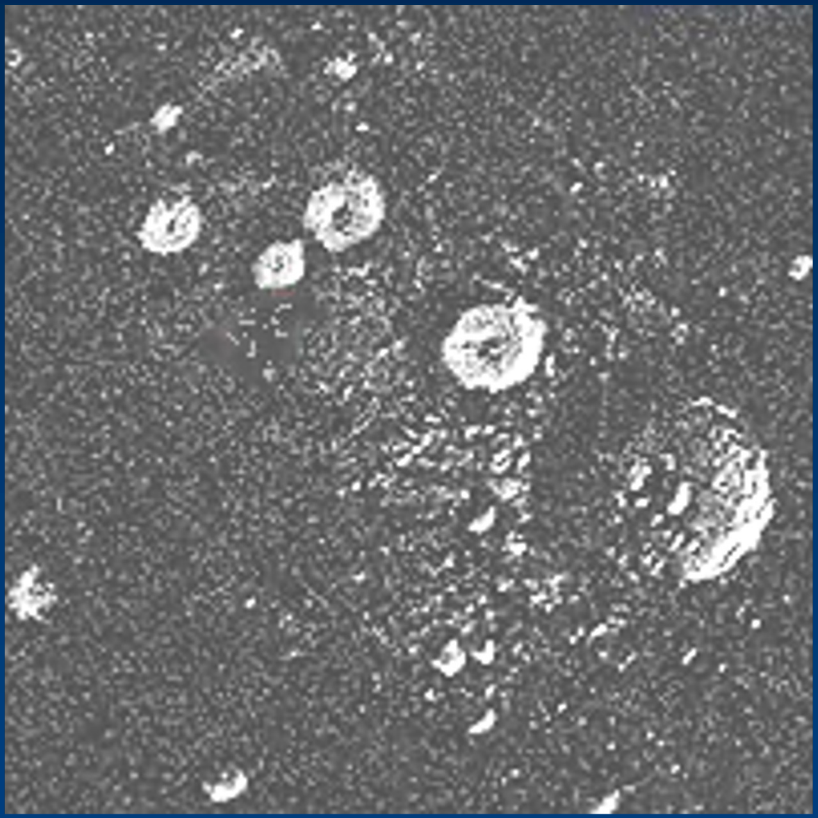
Can water exist on Mercury?

VLA, MESSENGER evidence

VLA mapping radar from Goldstone



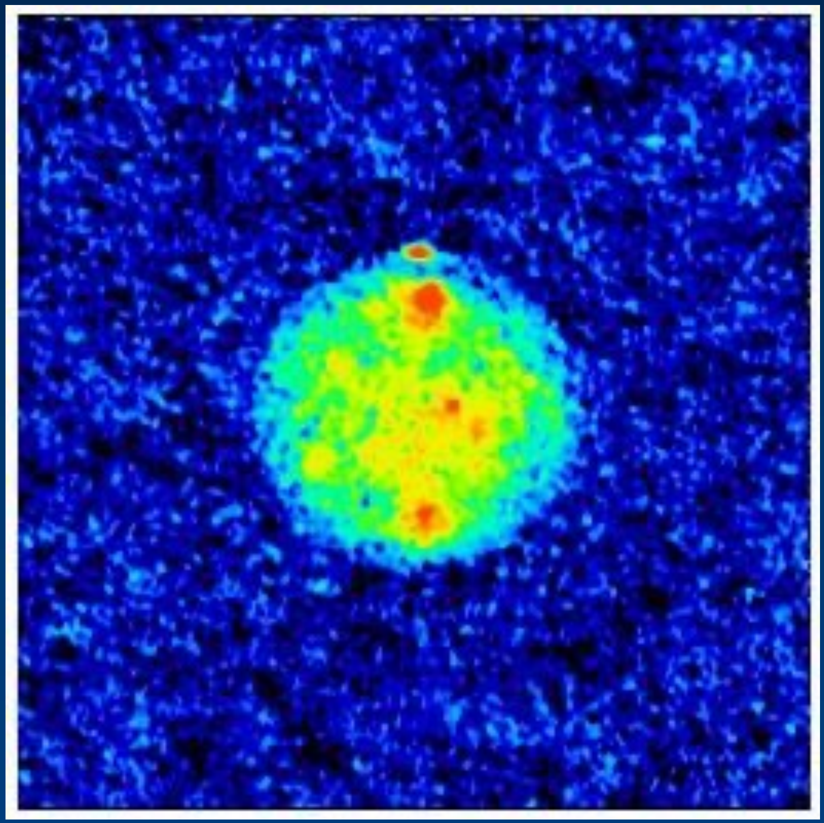
MESSENGER radar



- Ice in polar craters seen? Strong radar echo.
- If ice, where did it come from? May be from bombardment, or outgassing

Radar reflection

- 1991: Polar regions highly reflective
- 'Normal' ice usually absorbs radio waves, but at cold temperatures water ice is highly reflective
- Similar to what is seen on Mars and icy moons of Jupiter



Map made with the VLA telescopes.

Mercury evolution

1. Accumulation of solid material, not much light elements in the inner Solar Nebula. Differentiation, then cooling. No atmosphere (otherwise early distortion by weather & winds)

2. Heavy bombardment, ending close to Caloris event. Intercrater areas and scarps between 1 and 2. About 4 Gyrs ago.

3. Some volcanic activity, filling craters

4. Then, 3Gyrs ago a geologically dead period began

Cratering rates

Small meteroids common, large ones rare.
So same true for craters:

Crater size	Occurrence
10 km	every 10 million years
1 m	every month

If no other processes (erosion, lava flows) change the surface, the number of craters in an area tells you the age of the surface.

The effects of tidal forces

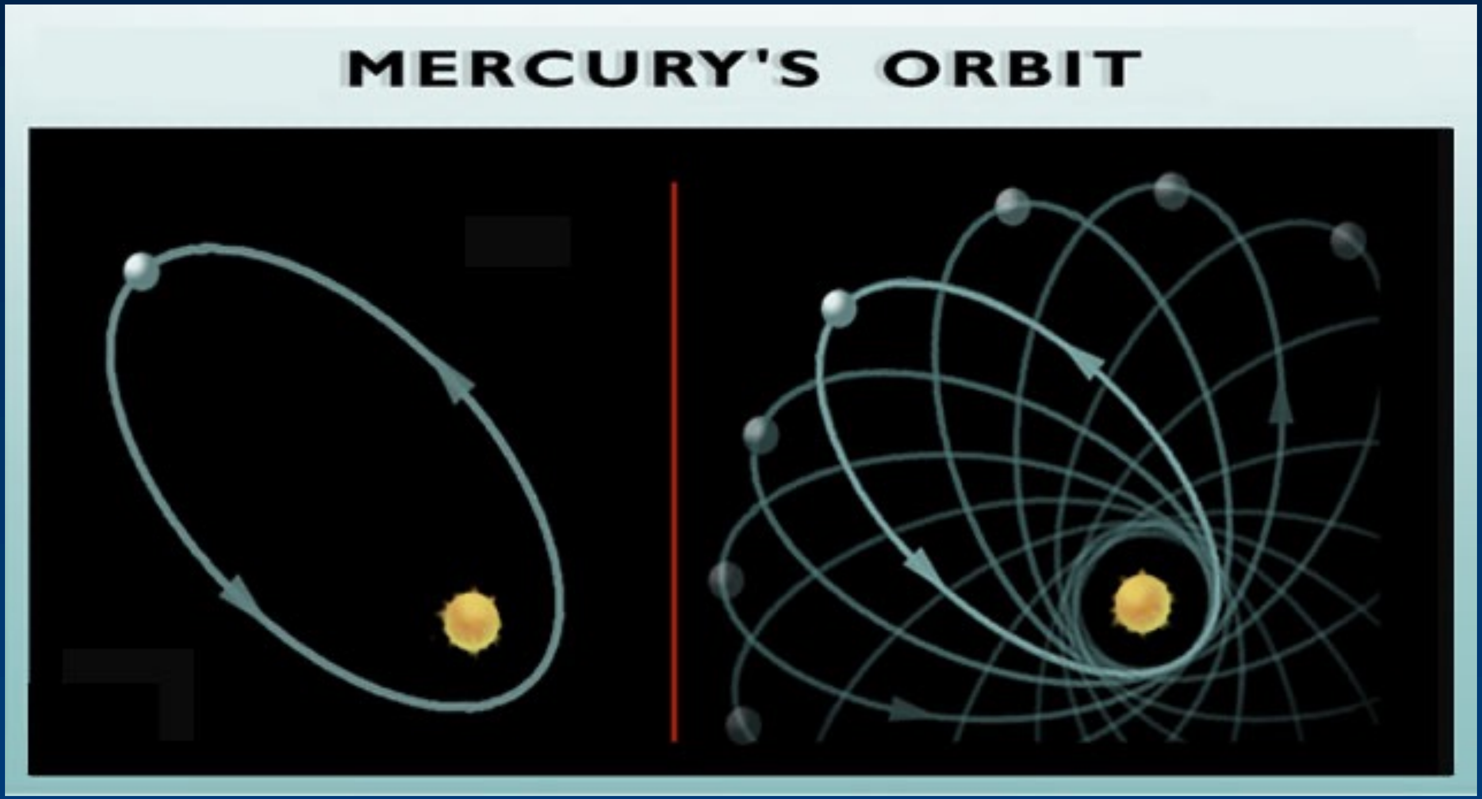
Earth is 80 times as massive as Moon => Earth's tidal effects on Moon are large.

⇒ The Moon is elongated toward the Earth.

⇒ Rotation rate tidally locked to its rate of revolution

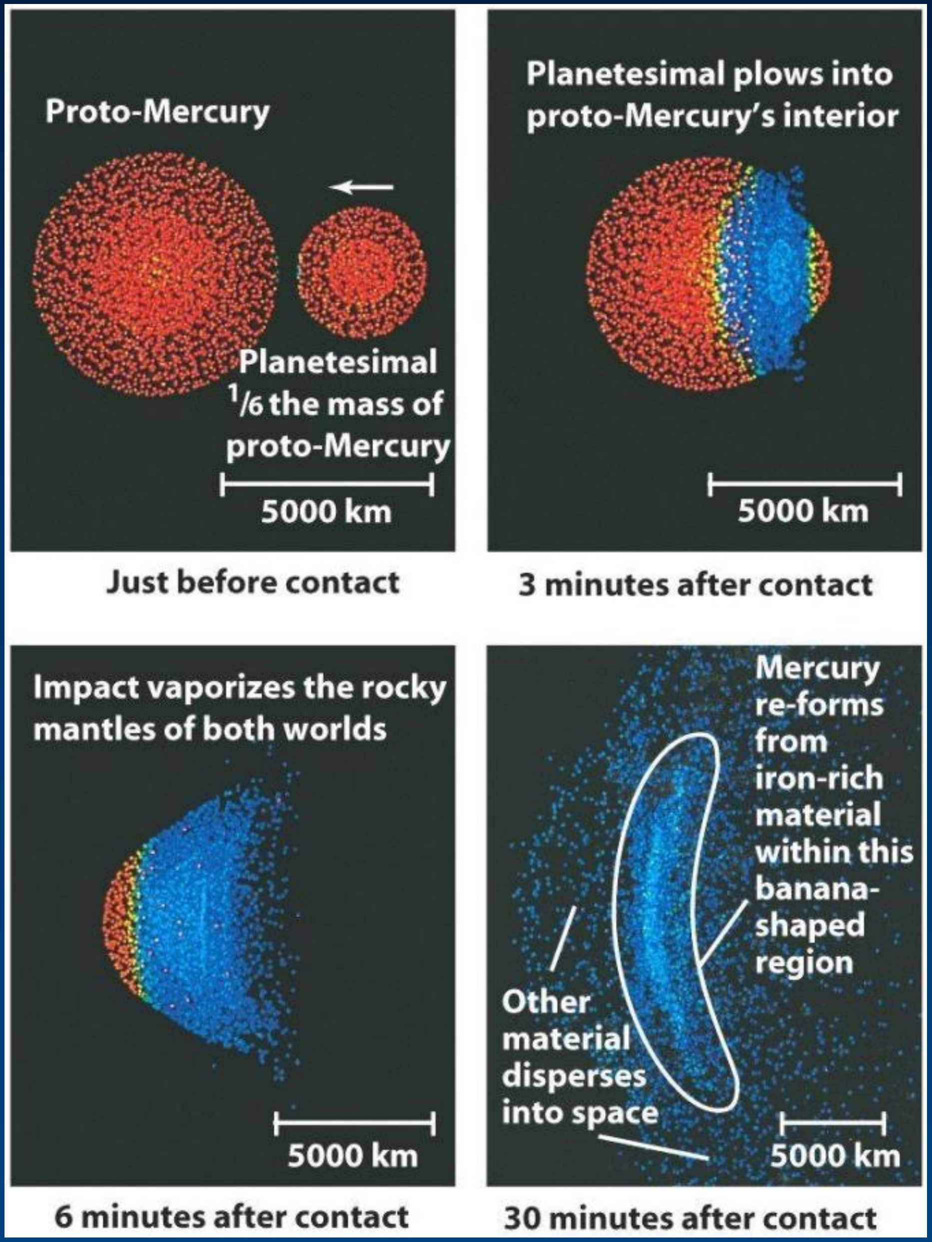
⇒ Moon is moving away from the Earth

Precession of the perihelion



- Estimates including effects of other planets were still 43 arcseconds/century off!
- A planet, Vulcan, was searched for but never found.

Answer: Einstein's general theory of relativity



Proto-Mercury collided head-on with a large body (although smaller than Mercury).

Impact blew off most of the mantle: left-over planet is a huge iron core.

Impacts are essential elements in the Solar System history!