MERCURY

Problem set #2 due now!

MERCURY

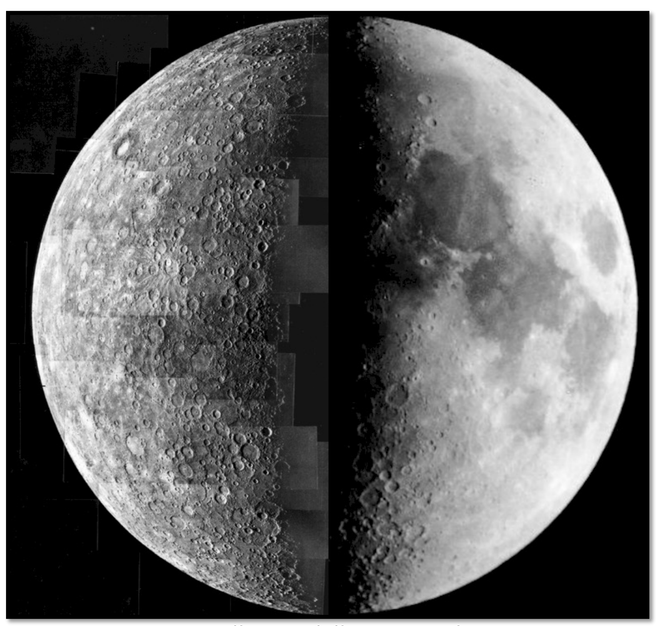
Properties of Mercury

Comparison of Mercury and the Moon

Water on Mercury and the Moon

Ice in the polar craters of Mercury and the Moon

Tidal locking and the eccentric orbits of the Moon

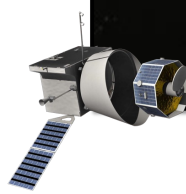


Half Mercury, half Moon (Image from Mariner 10, NASA)

VISITS TO MERCURY

There have been three:

- NASA's Mariner 10 conducted three close fly-bys in 1974-1975.
- NASA's MESSENGER (MErcury Surface, Space ENvironment, GEochemistry and Ranging) Satellite orbited with Mercury for more than four years before crashing into the planet's surface on April 30, 2015.
- *BepiColombo* (ESA/JAXA) has had six Mercury flybys and will next enter orbit around Mercury in November 2026.

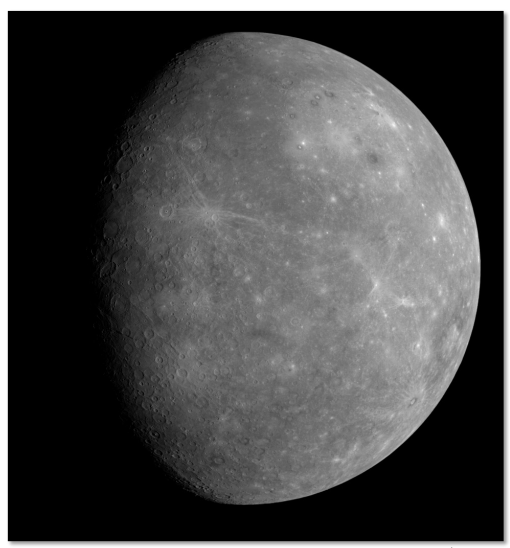


MESSENGER displays its scientific instrument complement as it passes by (NASA/JHU-APL)

Mariner 10

MERCURY'S VITAL STATISTICS

Mass	3.302×10^{26} g $(0.055M_{\oplus})$
Equatorial radius	2.4397×10^{8} cm $(0.383R_{\oplus})$
Average density	5.427 g/cm^3
Albedo	0.12
Average surface temperature	442.5 K
Orbital semimajor axis	5.791×10^{12} cm (0.387 AU)
Orbital eccentricity	0.2056
Sidereal revolution period	87.969 days
Sidereal rotation period	58.785 days



MESSENGER (JHU-APL/NASA)

MOON VS. MERCURY

	Moon	Mercury
Mass [g]	7.349×10^{25}	3.302×10^{26}
Radius [cm]	1.7381×10^{8}	2.4397×10^{8}
Mean density [g/cm^3]	3.350	5.427
Albedo	0.12	0.12
Mean temperature [K]	274.5	442.5
Orbital semimajor axis [cm]	3.844×10^{10}	5.791×10^{12}
Orbital eccentricity	0.0549	0.2056
Obliquity to Solar orbit	$1.54°$	$0.04°$
Tidally-locked rotation?	Yes	Yes
Mean surface magnetic field [G]	0	3.0×10^{-3}
Atmosphere	None	None
Surface visited?	Yes	Almost!

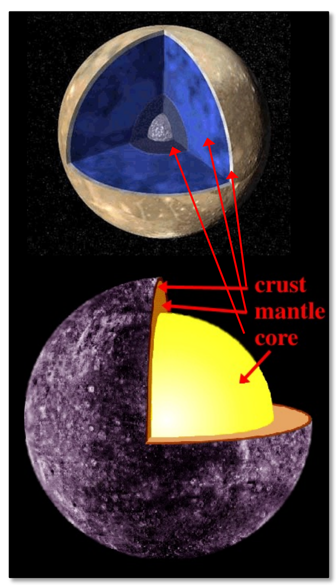
MOON VS. MERCURY

From the appearance, albedo, and reflectance spectra, we conclude that the surfaces are similar in composition: feldspar and pyroxene–bearing rocks.

From the density, we conclude that Mercury has more than its share of iron, in the form of a core with a radius about ¾ that of the planet.

From the magnetic field, we conclude that Mercury's core is probably liquid for a **dynamo** mechanism to operate.

- Mercury's magnetic field is a little more than 1% as strong as Earth's.



Diagrams by UCAR (U. Michigan)

PLANETARY BODY TEMPERATURES

All planetary bodies gradually cool over time as a result of heat transfer and radiative loss, because internal heat sources cannot be replenished.

This causes the **lithosphere** (outer, rigid layer of the mantle that conducts heat via conduction) to thicken as the size of the **asthenosphere** (inner layer of the mantle that conducts heat via convection) shrinks.

- Proceeds more rapidly for smaller bodies
- Volcanic and tectonic activities will also diminish

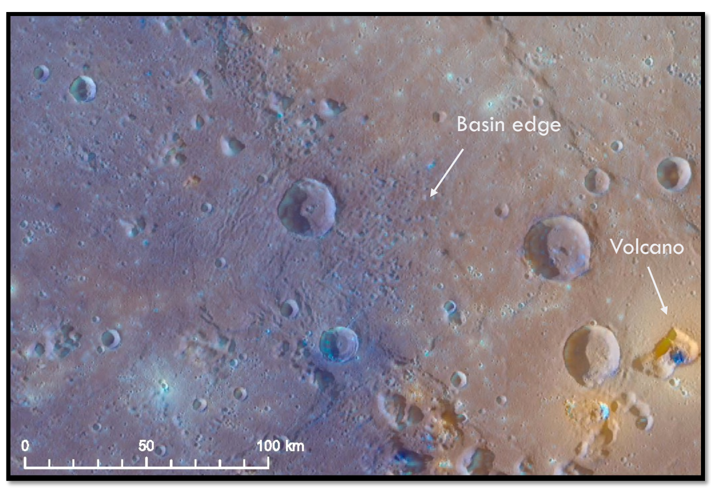
If the cooling proceeds to the point where the asthenosphere no longer convects, then the entire mantle becomes the lithosphere.

The timing of this process depends on the body's composition and size.

TECTONIC ACTIVITY: MERCURY V. MOON

From observations of rilles and scarps, we conclude that both have a "plastic" mantle, but Mercury has been tectonically active and the Moon has not.

Recently, volcanoes have been seen on Mercury within the giant Caloris impact basin. The Moon has none.



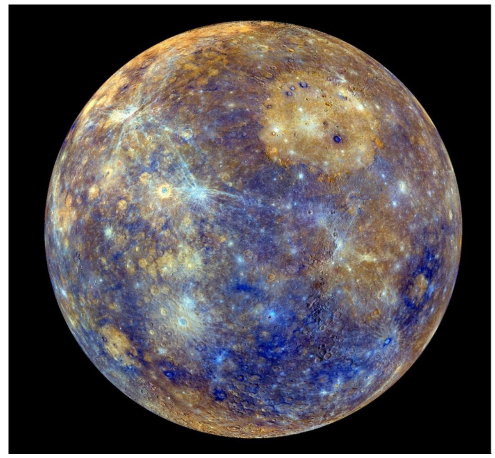
MESSENGER (JHU-APL/NASA)

SURFACE FEATURES OF MERCURY

Mercury's surface consists of **highlands** and **lowland plains.**

- The highlands consist of heavily cratered areas mixed with **intercrater plains,** relatively smooth clearings.

Heavily cratered regions contain fewer craters than the Moon, especially at small scales (< 50 km). This is most likely due to early major resurfacing, preferentially filling the smallest craters (the source of the intercrater plains).



WATER ON AIRLESS SOLAR SYSTEM BODIES

It is easy for lightweight atoms like hydrogen to escape from small bodies like the Moon and Mercury, and easy for sunlight to dissociate water into H and O. So, is there any water at or just underneath the surface of Mercury and the Moon? There are two good reasons to think that there should be, despite the difficulties:

1. **The solar wind and micrometeorites.** The Sun spews about $10^{-14} M_{\odot}/\mathrm{yr}$ in the form of the Solar wind and coronal mass ejections, mostly as protons and electrons. The planets also swim through a thin background of small dust grains (< 1 mm), 80% of which come from comet tails.
   - Traveling at high speeds, the protons bury themselves several cm below an airless surface that they encounter.
   - It does not take long for each proton to become (neutral) H, nor for two of these to make water with a nearby O.
   - From other directions, interplanetary dust includes cometary/asteroidal ice, directly adding water. Earth, for example, accretes such dust at the rate of 1.3×10^{10} g/yr (Rojas et al., 2021).

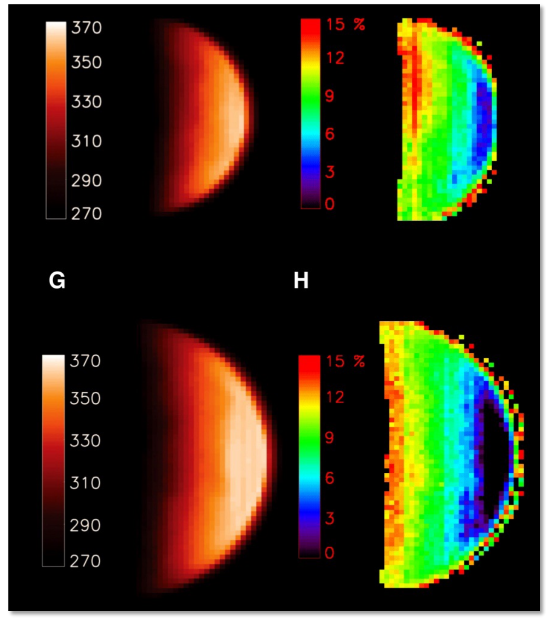
WATER ON AIRLESS SOLAR SYSTEM BODIES

This is probably the origin of the water detected on the Moon by the NASA *Deep Impact* and ISRO *Chandrayaan-1* spacecraft, and which has been found trapped in the Apollo regolith samples (Liu et al., 2012).

- Wha i's closest to the surface seems to come and go with darkness and sunlight, as shown on the right.

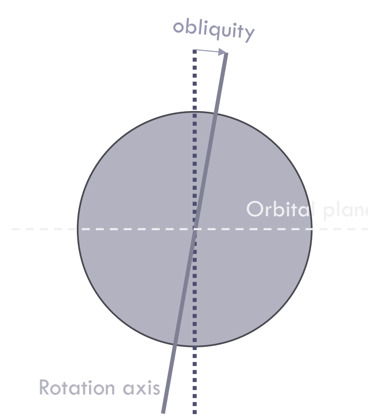
The amount detected is about 1-7% as much as Earth's driest deserts, such as Chile's Atacama Desert (Calderon et al., 2014).

Temperature (left) and water concentration (right) on the Moon one quarter of a lunar day apart. From Jessica Sunshine and the EPOXI team.



POLAR ICE: MERCURY V. MOON

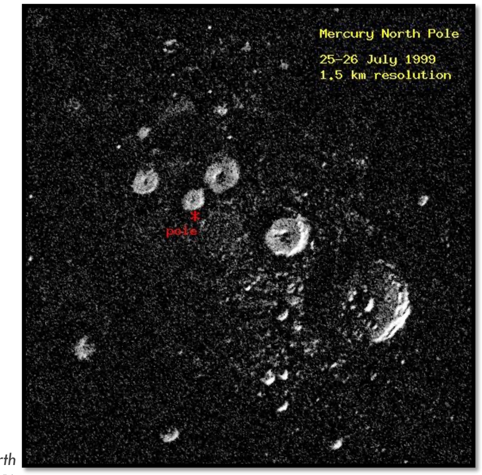
2. **Comet and asteroid impacts.** In principle, comets and asteroids could deliver larger amounts of water to the Moon and Mercury than the Solar wind and interplanetary dust can.
   - It would not last long in the sunlight on either body – it would evaporate, dissociate, and the hydrogen would quickly escape.
   - But because the Moon and Mercury both have very small **obliquity** (tilt of rotation axis from the orbital axis), there are **permanently shaded parts of craters** near the north and south poles, where some of the delivered water can last – in Mercury's case, practically forever.
     - In Mercury's case, it would last practically forever: there is no natural pathway for the planet to change its obliquity (unlike the Moon, which has Earth nearby to shove it around).



POLAR ICE: OBSERVATIONS WITH ARECIBO

In 1999, radio astronomers at the Arecibo Observatory made a long-wavelength, radar-polarimetric study of the north pole of Mercury and found that the perpetually-shadowed crater floors were very reflective in a way most easily explained by clean water ice.

For ice detection, this technique is less controversial than other means previously employed on the Moon. But it was shocking nonetheless: ice on Mercury?



Radar-reflectivity image of the north pole of Mercury (Harmon et al. 2001)

POLAR ICE: ARECIBO AND THE MOON

Arecibo also tried to confirm previous "detections" of water ice on the Moon. They were able to show that there is not any surface ice in the Moon's polar craters.

Recently confirmed from space by the JAXA *Kaguya*/SELENE and NASA LRO satellites.

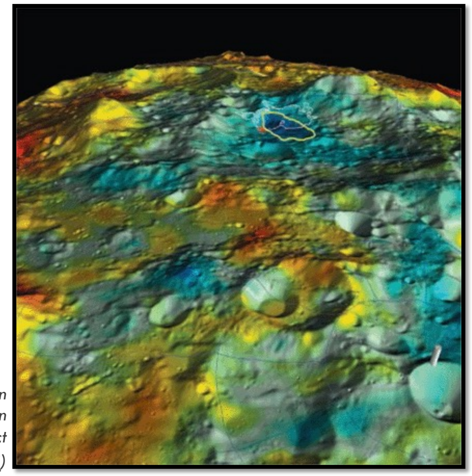
Radar image of the Moon's south pole (N.J.S. Stacy, PhD dissertation, Cornell U.)

POLAR ICE: BELOW THE SURFACE

What about subsurface ice mixed with dirt in the permanently-shadowed Lunar polar craters? To expose this was the job of NASA's Lunar Crater Observation and Sensing Satellite (LCROSS)

Make a small crater within a permanently-shadowed region with the impact of a spent rocket stage.

Analyze the composition of the ejecta from measurements by satellites directly overhead.



A permanent shadow on the Moon (yellow contour) compared to neutron signal (blue) and the LCROSS impact site (red dot). (NASA and ISR/RAS)

POLAR ICE: RESULTS FROM LCROSS

Results show water ice present at the level of about 50 liters of water per ton of ejecta in this polar-crater floor.

This would be on the high end of soil water content for the driest deserts on Earth, 2-5 times the Atacama.

There is as much molecular hydrogen (H_2) in the soil as water ice, molecule for molecule. Much of the neutron signal was from this H_2.

The water ice comes with very large amounts of other volatiles like CO, calcium, magnesium, and mercury.

Species	Abundance in ejecta (percent by mass)
H_2O	5.4
H_2	1.4
CO	5.7
Hg	1.2
Ca	1.6
Mg	0.4

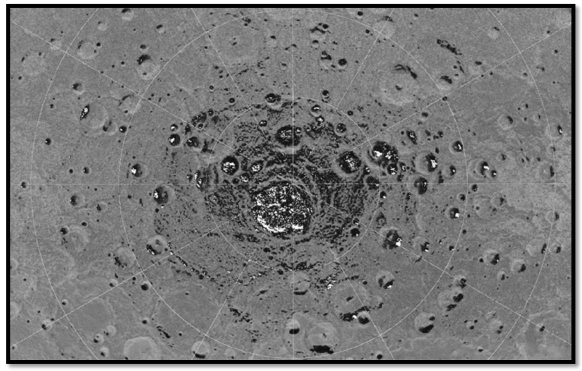
Colaprete et al. (2010), Gladstone et al. (2010)

POLAR ICE: COMPARISON TO PREVIOUS RESULTS

This amount of water is consistent with the Arecibo radar observations.

There is enough to be scientifically interesting, and the mixture of volatiles constrained models of delivery and the thermal history of the crater floors.

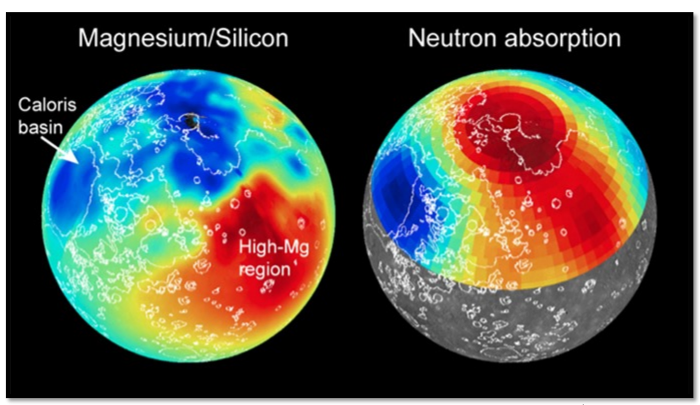
An entire permanently shaded region contains $10^6 - 10^7$ gallons, which would fill a large municipal water tower. This would go a long way toward the needs of a Lunar base, but it must be laboriously extracted and purified.



CHEMICAL COMPOSITION OF MERCURY’S SURFACE

Mercury formed from materials with less oxygen than those that formed the other terrestrial planets

- Surface depleted in Fe and Ti by an order of magnitude
- Mg/Si ratio is 2-3 times higher than the Moon and other terrestrial planets
- Al/Si and Ca/Si are half as large
- Extremely high amount of S/Si (volatile)



Surface chemistry maps (MESSENGER, JHU-APL/NASA)

TIDAL LOCKING FOR MERCURY AND THE MOON

Mercury and the Moon also have tidal locking in common.

In celestial mechanics, **tidal locking** means that the heat dissipated during an orbit, by variations in the **tidal forces,** is minimized.

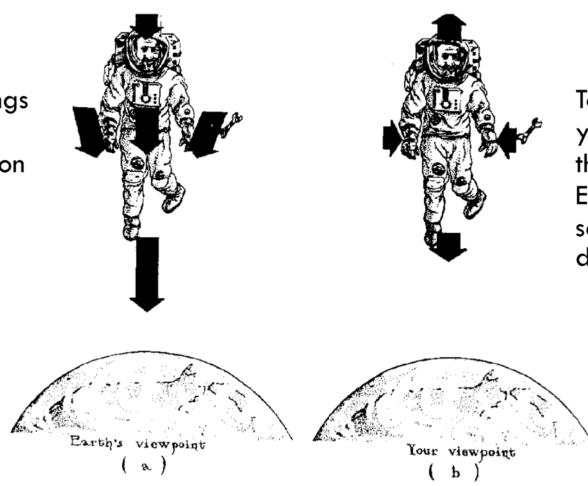
Tidal forces are the gravitational force differences between the near and far sides of a body due to their different distances away from a second body, and from one side to another of a body due to different directions toward the second body.

The result is a stretch along the line between the two bodies and a compression in the perpendicular directions.

We will derive formulas for tidal forces – and much more on tides – later this semester.

AN INTRODUCTION TO TIDAL FORCES

Earth pulls all things toward its center, and pulls harder on things which are closer.



To you, it seems as if you are stretched in the direction of the Earth's center and squeezed in the other direction.

Figure from Thorne, Black Holes and Time Warps

TIDAL LOCKING & THE MOON'S ORBIT

A body in circular orbit, with rotation period equal to revolution period, suffers no change in tidal forces as it travels its orbit. Thus, there is no heat dissipated from stretching and shrinking.

The Moon's orbit about Earth is not circular: it has an **eccentricity** $\varepsilon = 0.055$, so the stretch and compression varies as the Moon travels in its orbit.

This variable stretch and compression heats the Moon, whatever its rotation rate: the Moon is not elastic, so the stretching and squeezing encounter friction. (The added heat is radiated away, just as absorbed sunlight is.)

The minimum in the stretch/squeeze heat dissipation is once per orbit. This is why the Moon's rotation rate has slowed over time to equal its revolution rate.