Part 4: Our Solar System, Life in the Universe

Tuesday, April 11 — Reading: Chapter 15 (12th & 13th Edition of the textbook)
- Solar System: Introduction and Formation; Other Solar Systems

Thursday, April 13 — Reading: Chapter 18 (planets)
- Solar System: Jupiter, Saturn, Uranus, Neptune

Tuesday, April 18 — Reading: Chapter 18, 19
- Solar System: Outer Solar System, Pluto, Kuiper Belt, Comets, Satellites

Thursday, April 20 — Reading: Chapter 16, 17, 18, 19
- Solar System: Satellites, our Moon, Mercury, Asteroids

Tuesday, April 25 — Reading: Chapter 17
- Solar System: Mars and Venus

Thursday, April 27 — Reading: Chapter 16
- Solar System: Earth

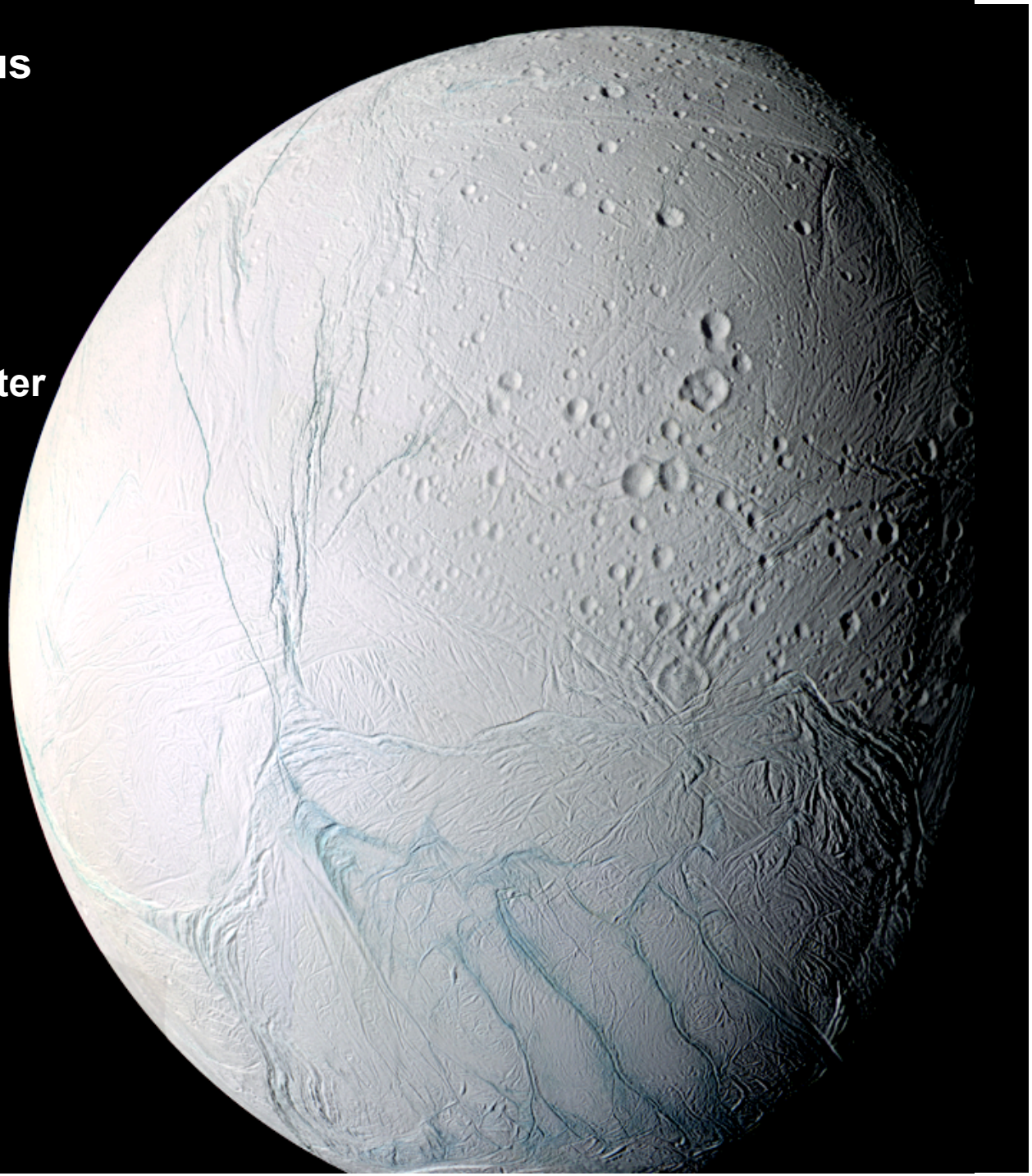
Monday, May 1 — Help Session from 4 to 6 PM in RLM 4.102

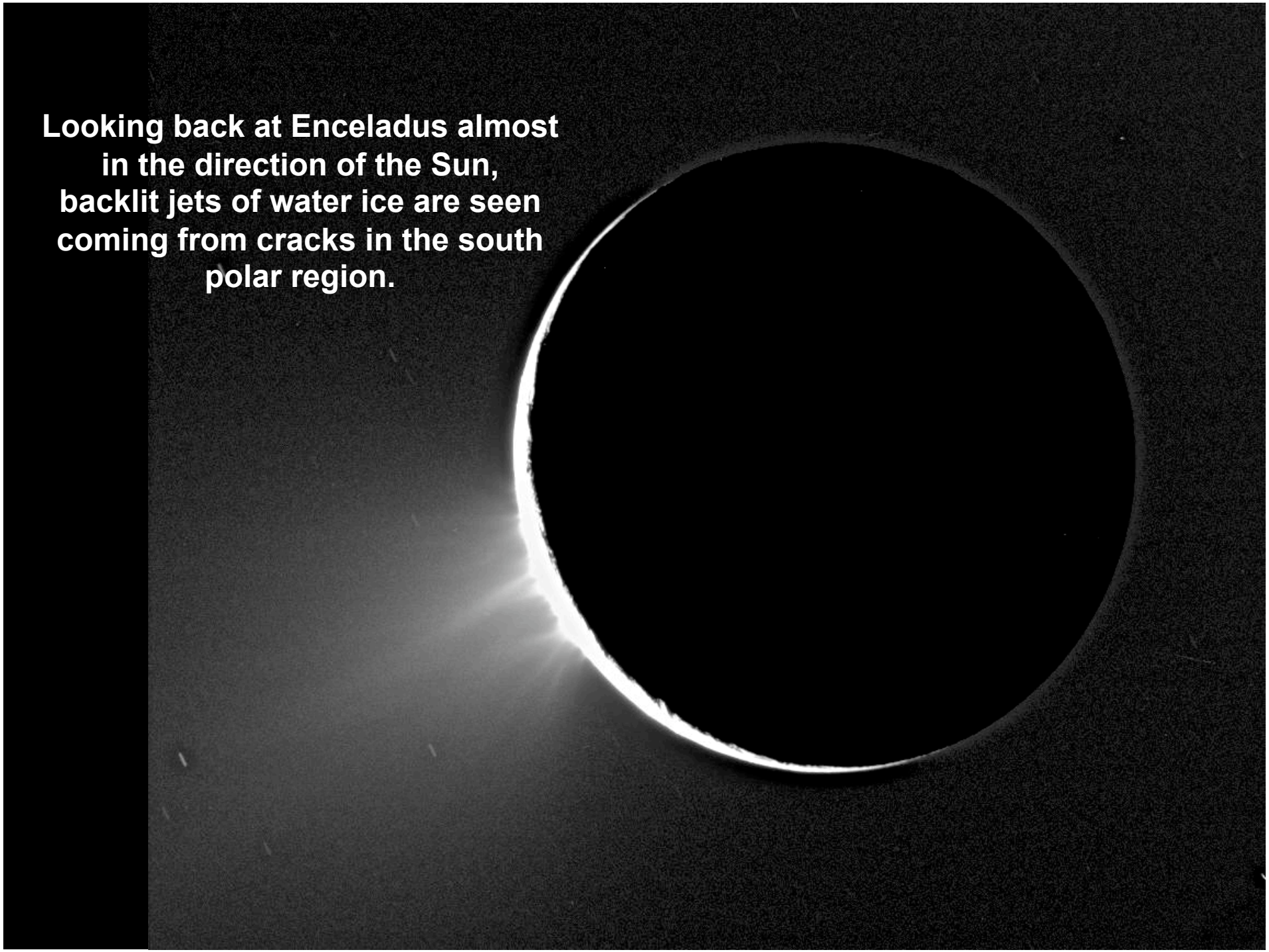
Tuesday, May 2 — Exam 6

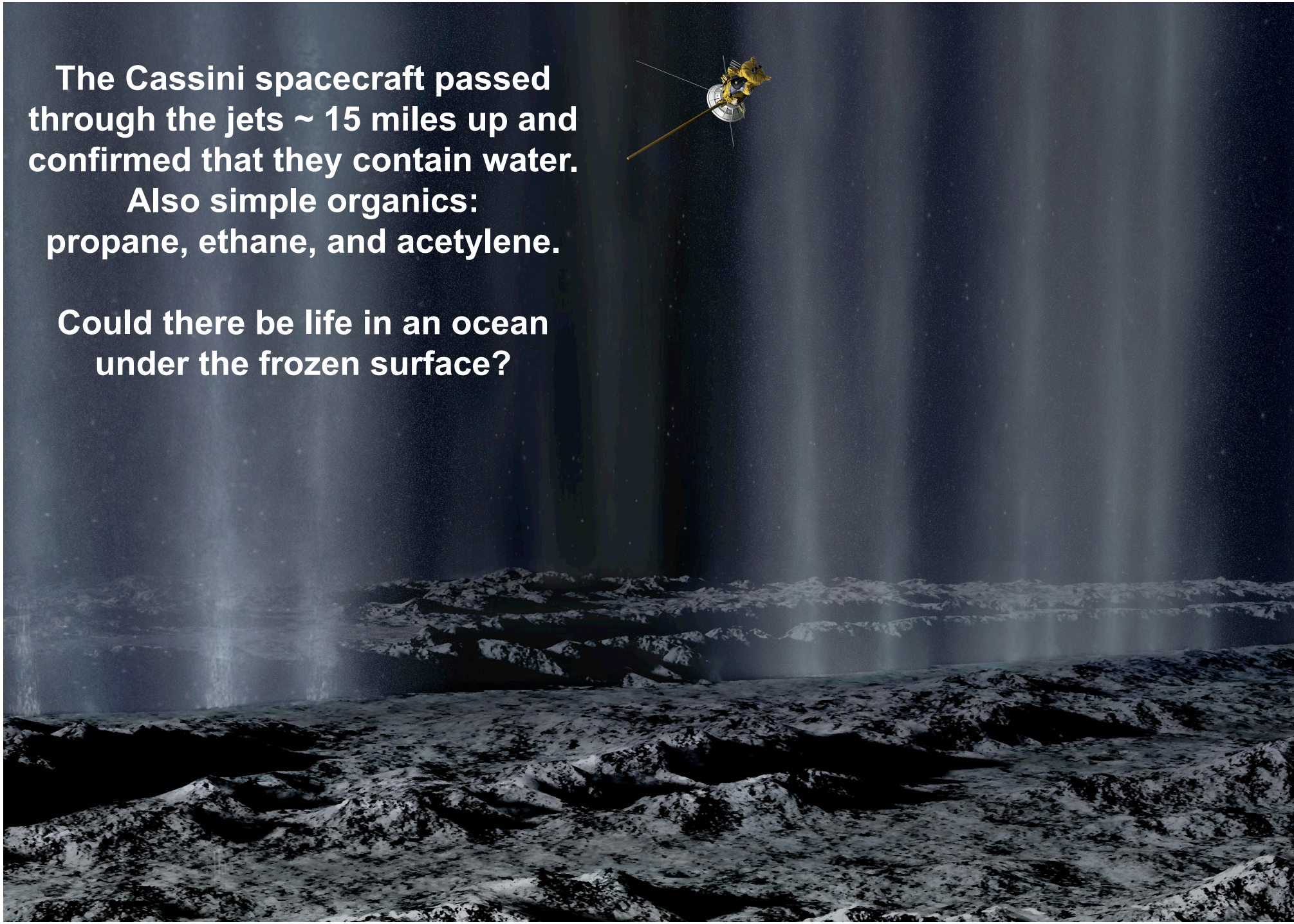
Thursday, May 4 — Reading: Chapter 20
- The history of life on Earth; Life in the Universe

Saturn's moon Enceladus (300 miles in diameter)

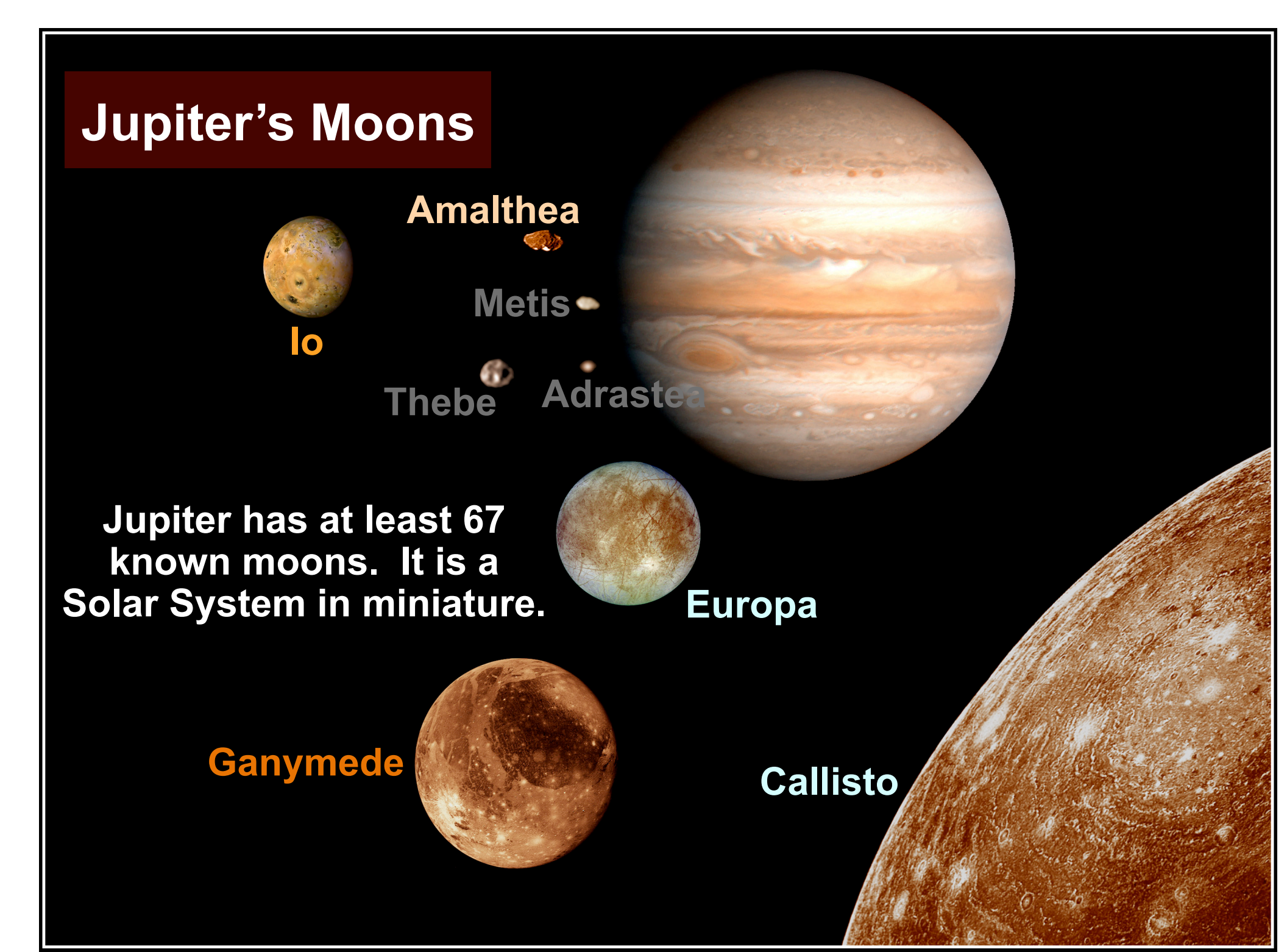
Jets of water ice have been observed to come from cracks in the south polar region. Therefore there is liquid water not far under the surface.



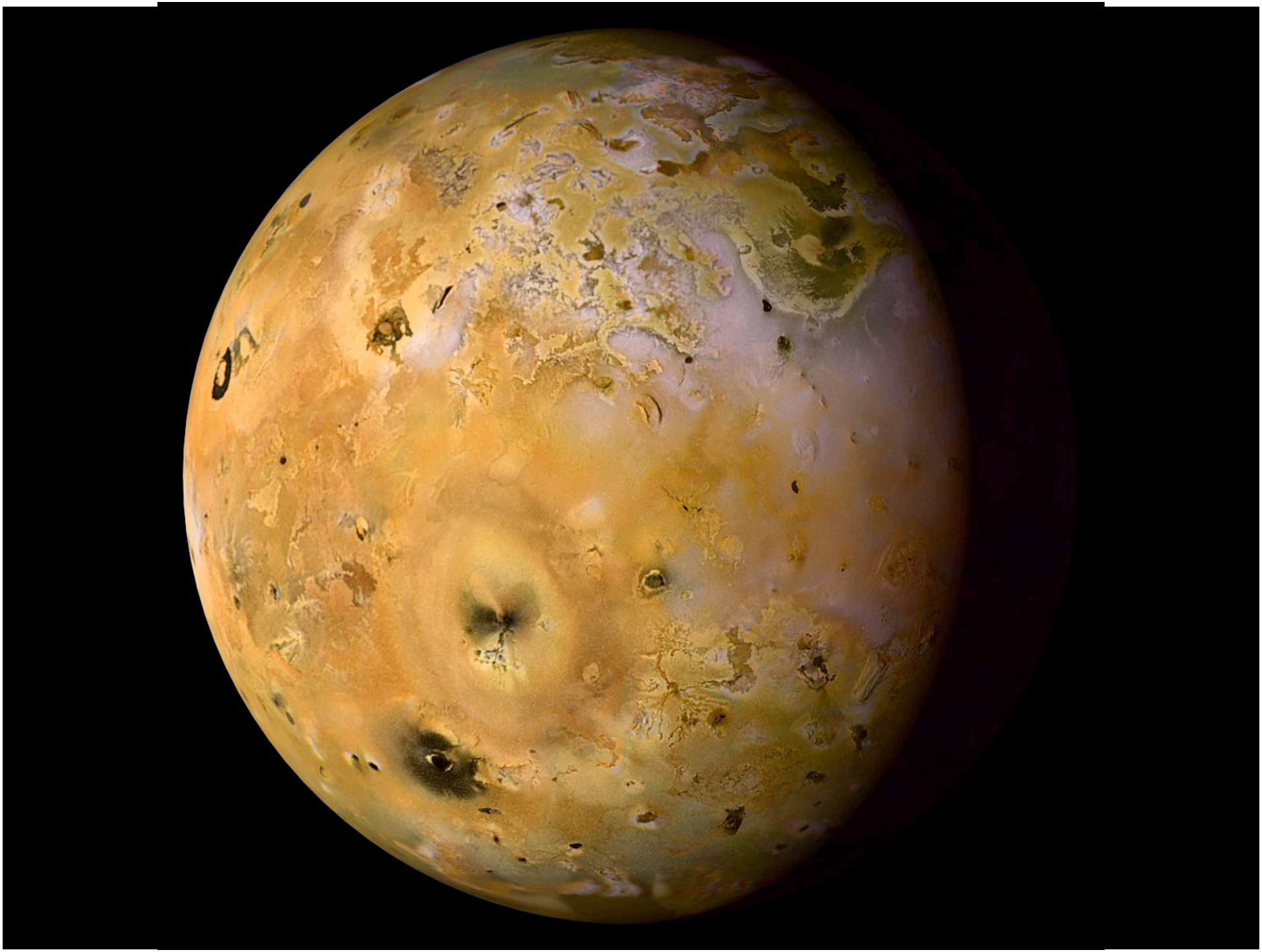

Looking back at Enceladus almost
in the direction of the Sun,
backlit jets of water ice are seen
coming from cracks in the south
polar region.


The Cassini spacecraft passed through the jets ~ 15 miles up and confirmed that they contain water.
Also simple organics:
propane, ethane, and acetylene.
Could there be life in an ocean under the frozen surface?

Jupiter's Moons

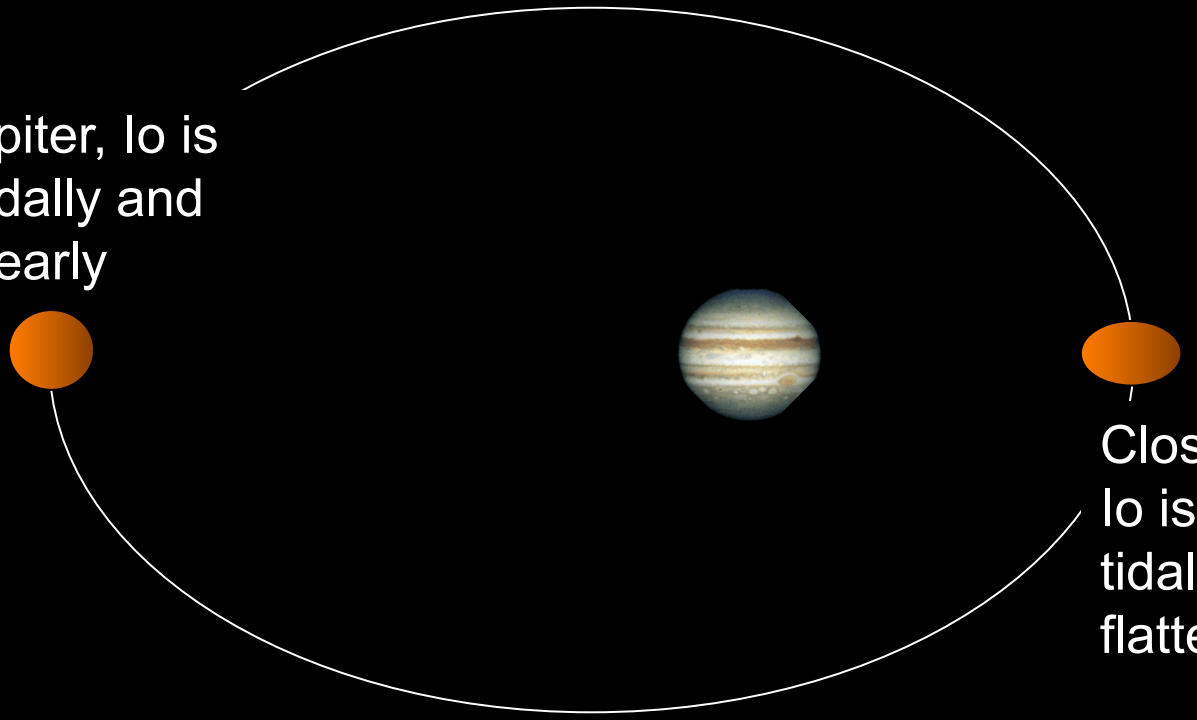


The Jupiter System

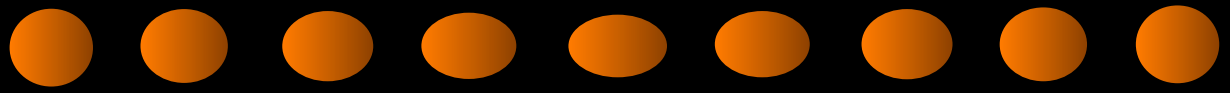


Io is the most volcanically active body in the Solar System.
Io's volcanoes are caused by tidal heating:

Farthest from Jupiter, Io is least stretched tidally and therefore most nearly spherical.

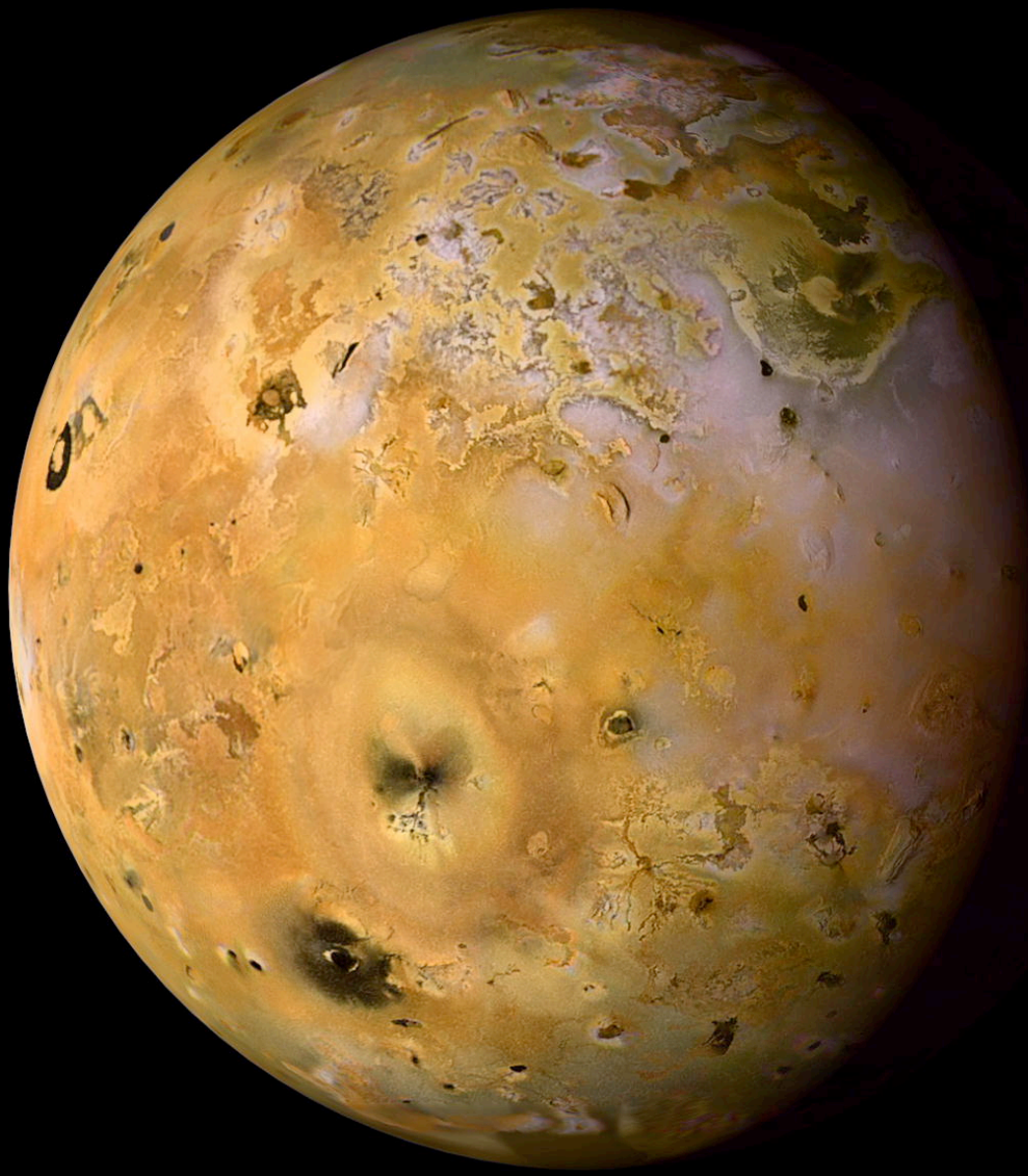


Close to Jupiter, Io is stretched tidally, so it is flattened.



If you do this to a rocky satellite, it <u>will</u> get hot!

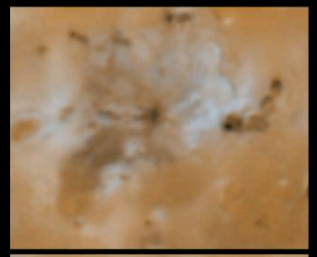
Io



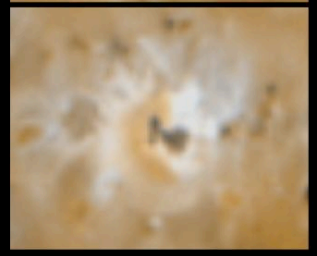
Io is the most volcanically active body in the Solar System. The reason is heating by tidal pumping. Io's orbit is slightly elliptical; when Io is close to Jupiter, it gets stretched, and when it is far from Jupiter, it rebounds. The tidal bulge is as high as 330 feet!

Over 300 volcanoes have been found. They resurface Io to a depth of 1 m every 1000 years. So Io has the youngest surface of any body in the Solar System. That's why we don't see impact craters.

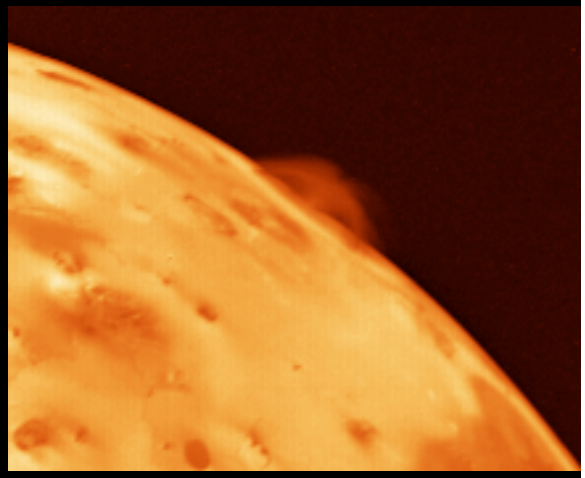
Volcanic Eruptions on Io



1979



1996



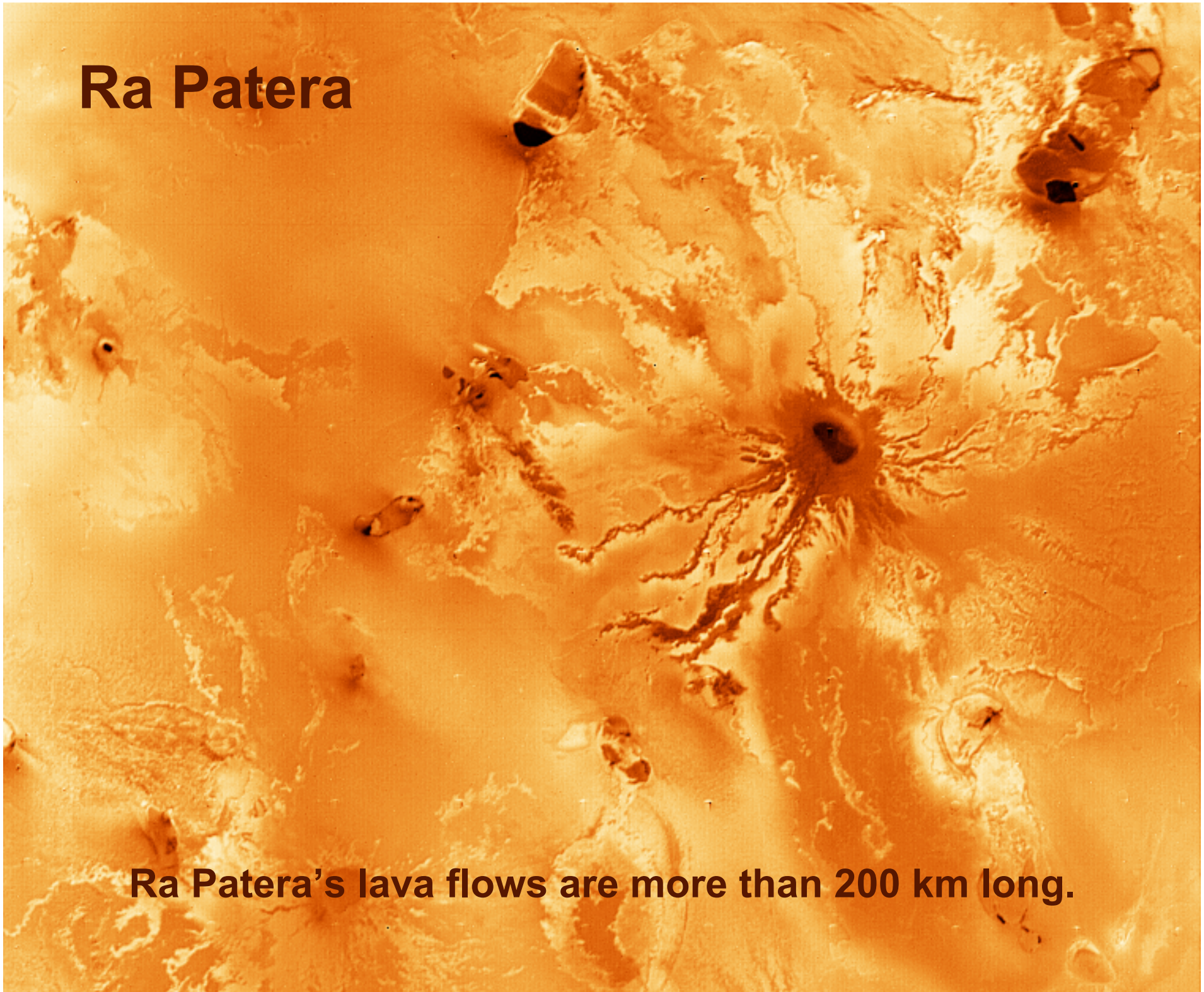
Eruption of Prometheus

Eruption of Ra Patera

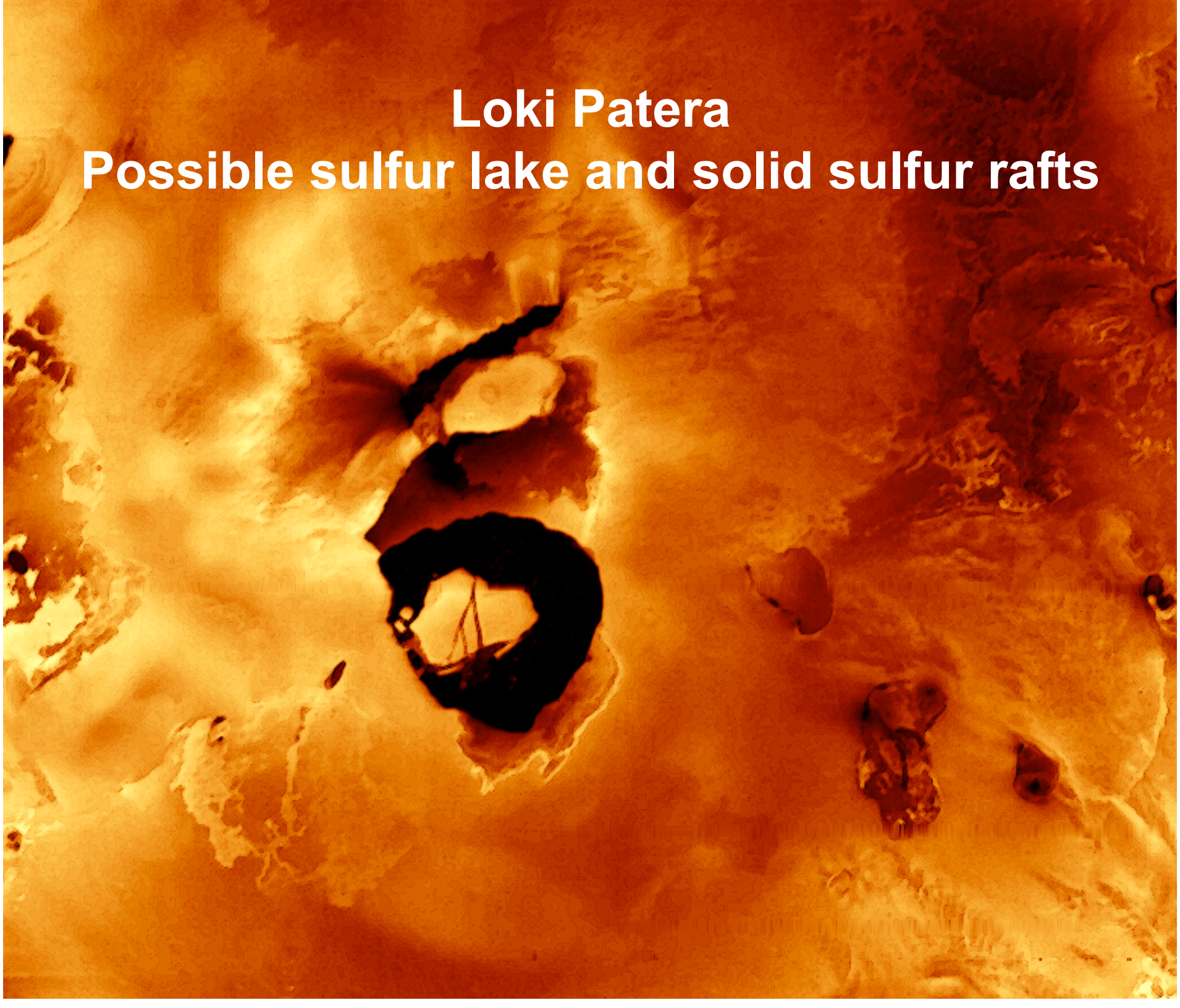
The volcanic plume is 60 miles high. Volcanic plumes on Earth are never this high because of Earth's higher gravity and thick atmosphere.

The insets show how Ra Patera changed in 17 years. An area the size of New Jersey was resurfaced with new lava.

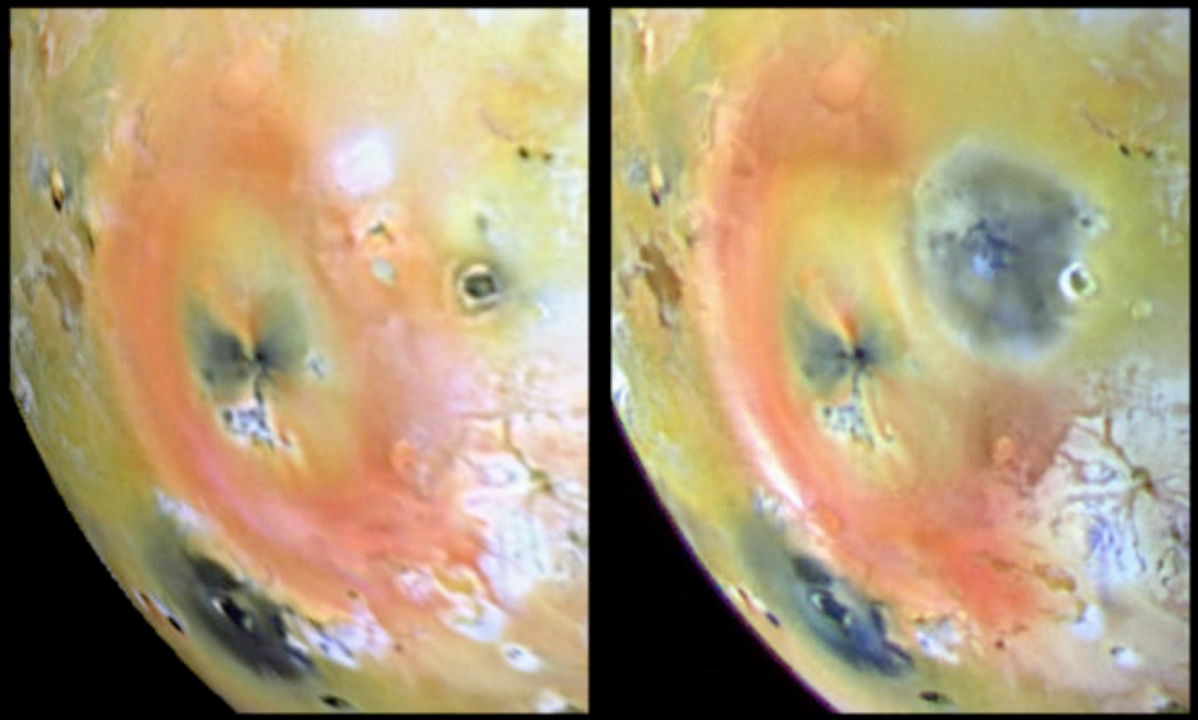
Ra Patera



Ra Patera's lava flows are more than 200 km long.


Loki Patera
Possible sulfur lake and solid sulfur rafts

Io's biggest volcano (Pele) and one of its newest (Pillan)



Pele is roughly the size of Alaska. Pillan is the size of Arizona.

Pillan formed over several months in summer 1987.

Pele — Glowing Lava Fountain and Caldera

Pele — Glowing Lava Fountain and Caldera

Kilauea Caldera, Hawaii

Halemaumau Caldera

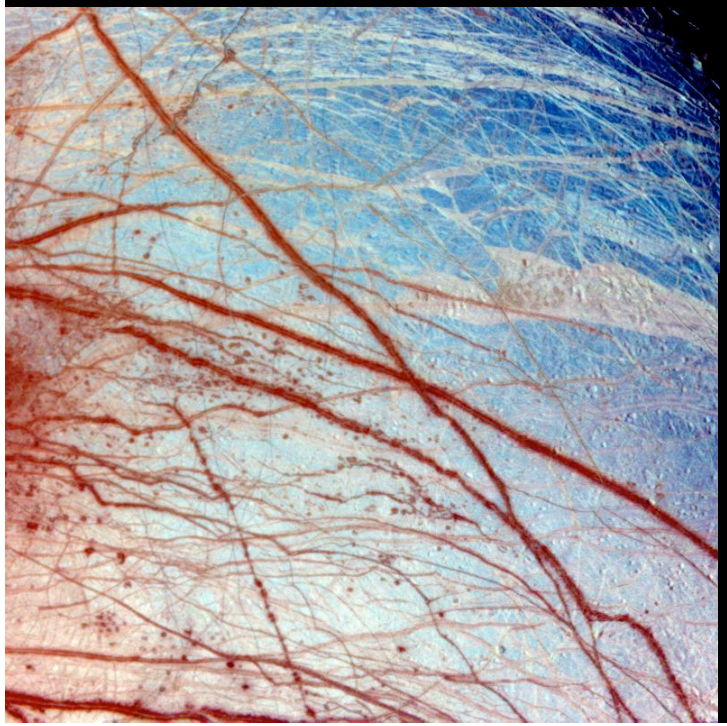
Pele — “Curtain of Fire” Eruption

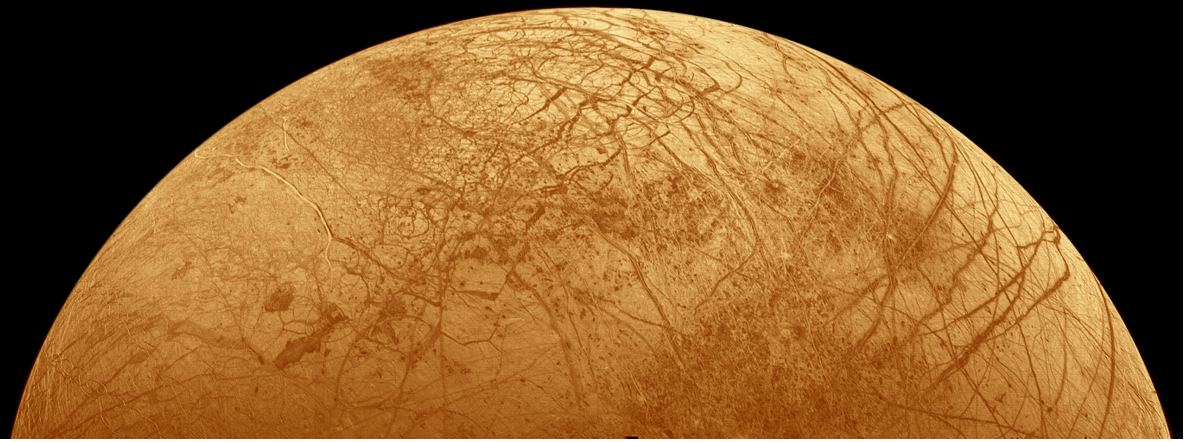
Pele — “Curtain of Fire” Eruption

“Curtain of Fire” Eruption, Kilauea, Hawaii
(January 1983 = Start of Current Eruption)

Europa

Europa has almost no craters or vertical relief. It looks like its features were painted on with a felt marker. Europa is warm inside — like Io — because of tidal heating by Jupiter. But Europa is heated 10 times less than Io. Models of its interior suggest that under a several-mile-thick crust of water ice, Europa has oceans as deep as 30 miles. Surface markings could be cracks in the ice that filled with “dirty” water and refroze. If there is an ocean, then Europa is one of the best places in the Solar System to look for life.

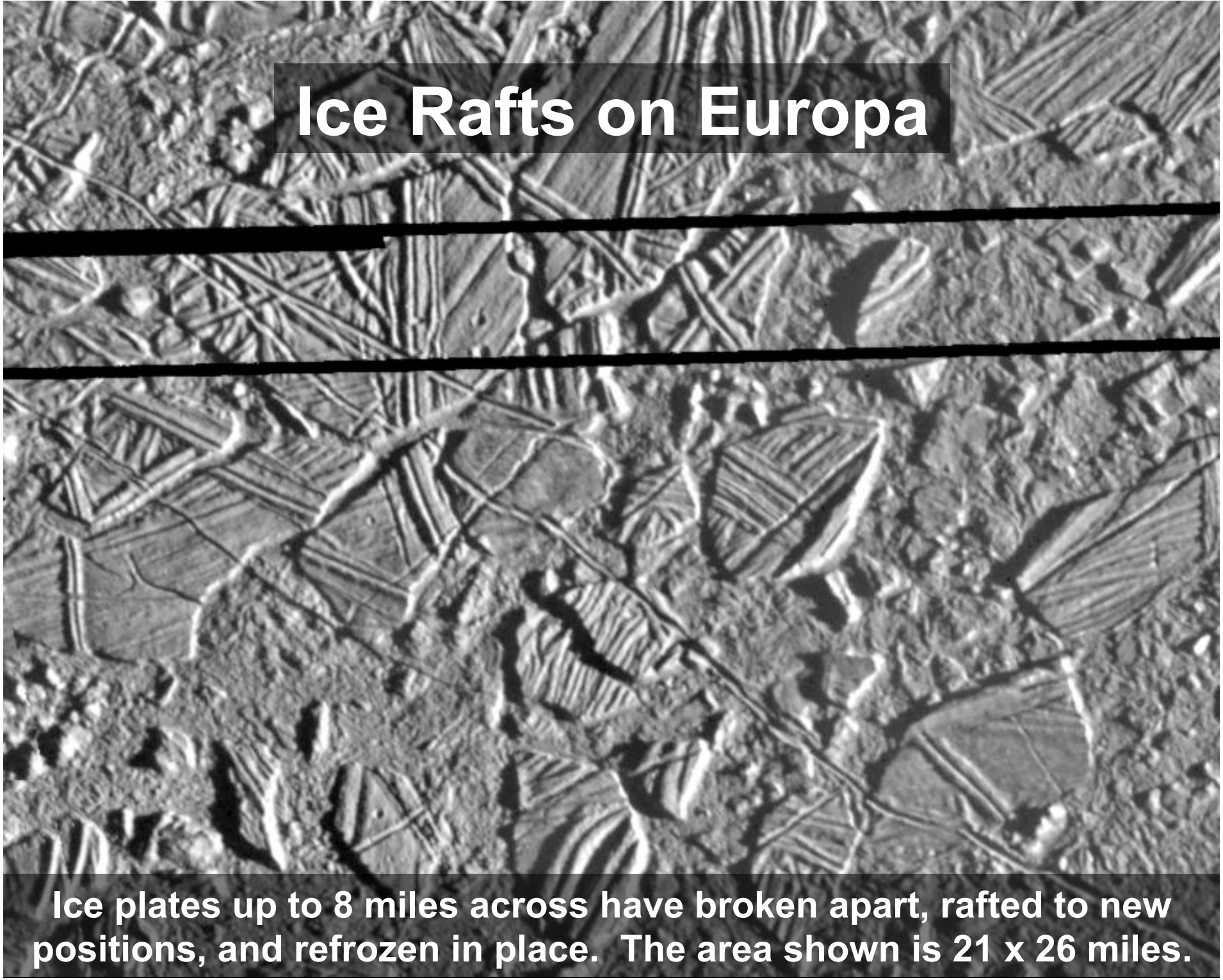




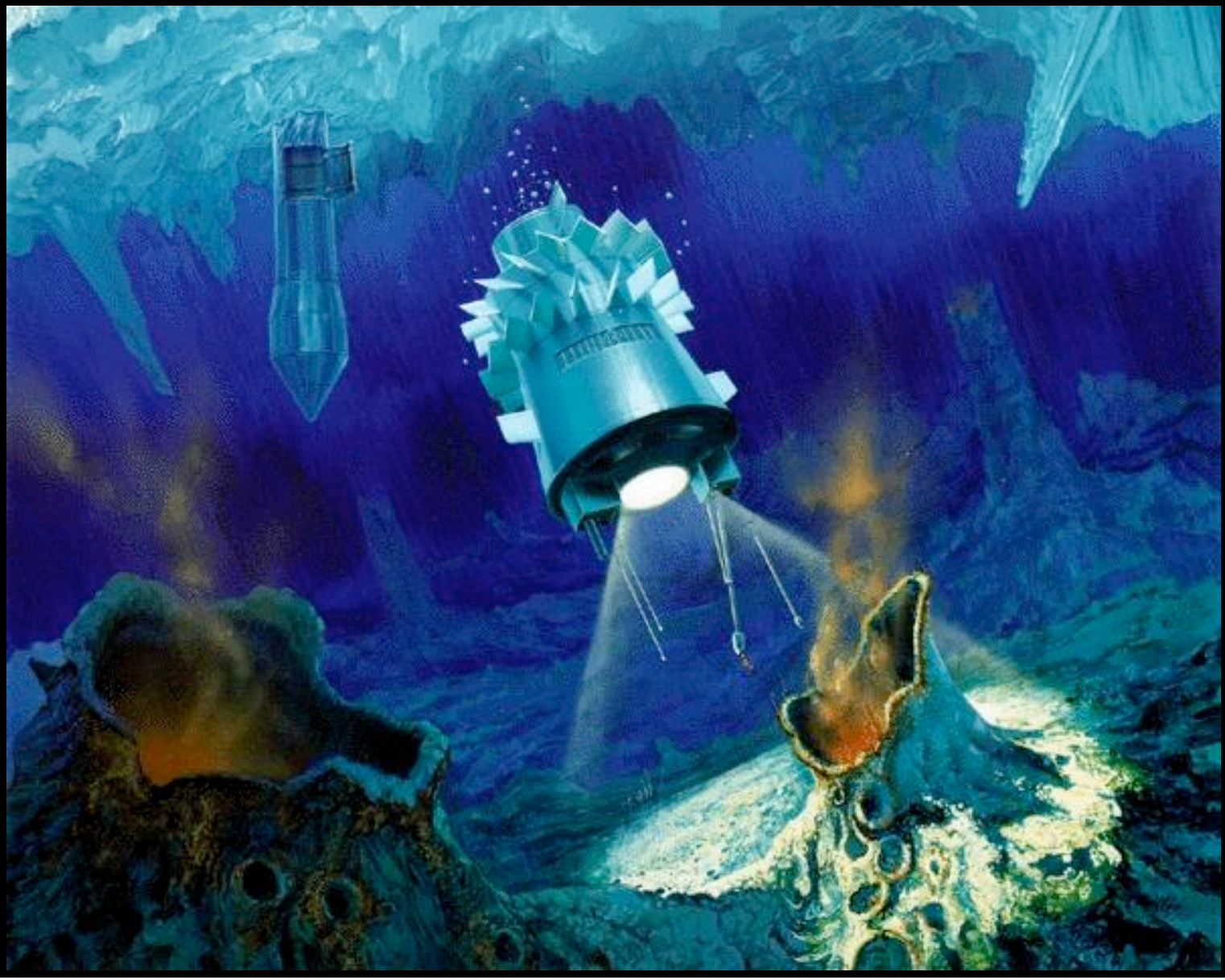
Europa

Ridge systems in an 81 x 87 mile region of the ice crust. The smallest features visible are the size of a city block.

This image was taken by the Galileo probe in February 1997. It was 11,000 miles away from Europa.

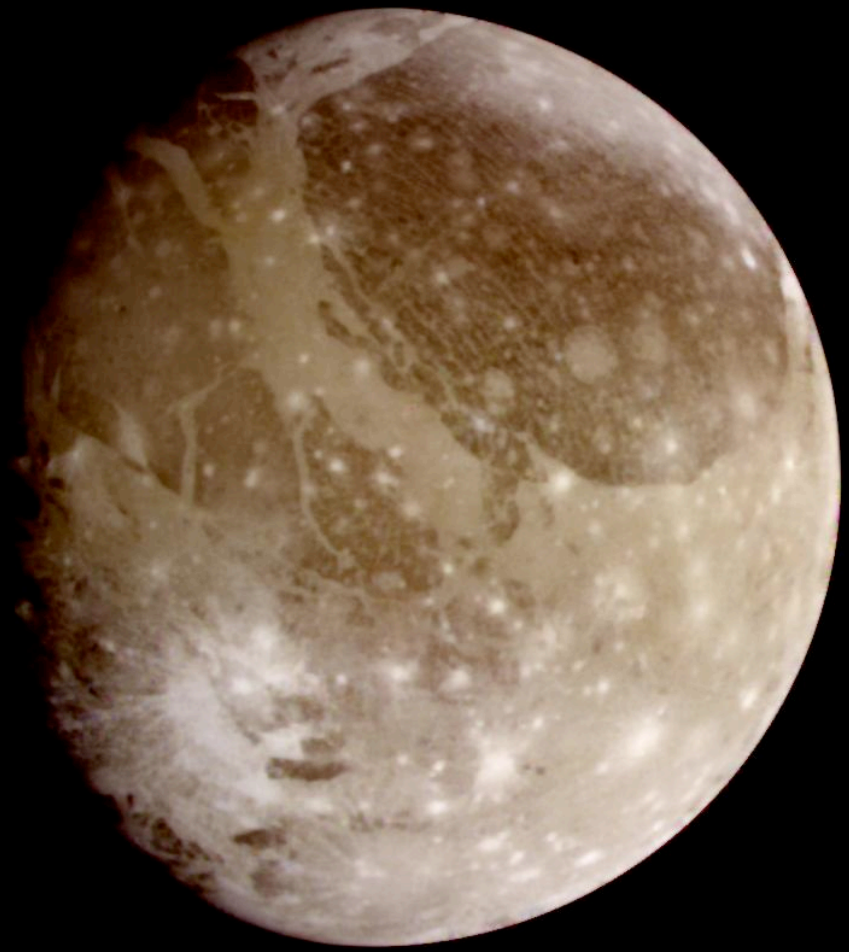

Ice Rafts on Europa
Ice plates up to 8 miles across have broken apart, rafted to new positions, and refrozen in place. The area shown is 21 x 26 miles.

Plans are being developed for an under-ice probe to look for life on Europa.

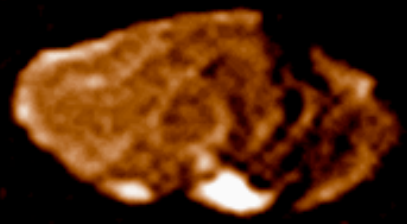


Ganymede is the biggest moon in the Solar System.

With a diameter of 3170 miles, it is bigger than Mercury (2930 miles).
Its surface is old and heavily cratered.



Amalthea



Amalthea is the biggest of Jupiter's small moons, at 160 x 100 x 90 miles. The local vertical relief is up to 12 miles. Amalthea is similar to other small moons and asteroids.

Amalthea's gravity is not strong enough to force the moon to have a spherical shape. Irregular, potato-like shapes are typical of small moons and asteroids.

The Moons of Mars: Deimos

Deimos is similar to most asteroids: it is a rock 10 x 7 x 7 miles in diameter.
It is heavily cratered, but the craters are smooth and partly filled in with debris.

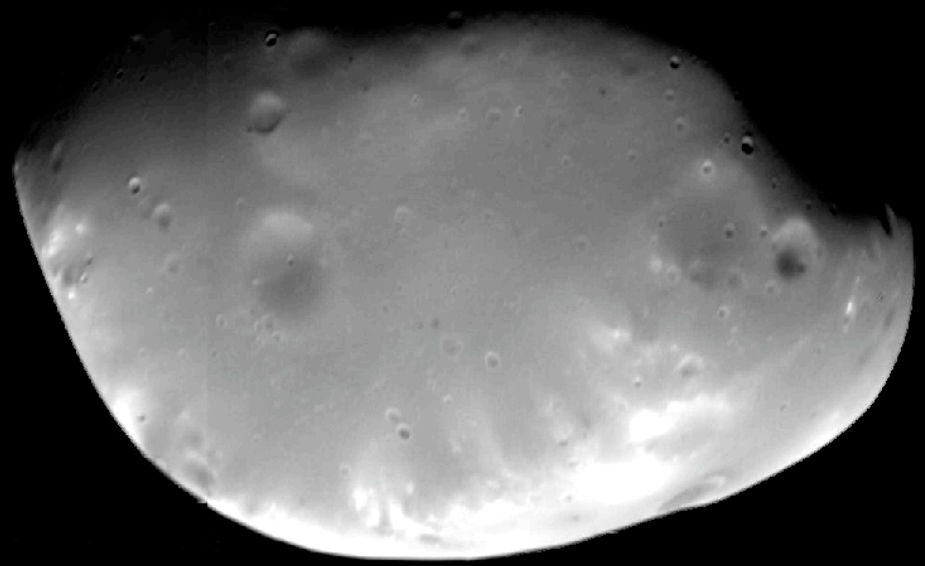
The surface orbital velocity is ~ 10 mph. The surface escape velocity is ~ 14 mph.
So you could easily throw a baseball into orbit around Deimos ... or completely away from the satellite.

If you dropped a rock from eye level (~ 5 ft) it would take 32 sec to fall to the ground.

You would weigh 0.5 oz per 100 lb on Earth!

If you can jump 1 foot up on Earth,
you could jump 3400 ft up on Deimos.
It would take 14 min to get that high.

Note:
Both Deimos and Phobos
are nonspherical, so the surface
gravity varies from place to place.



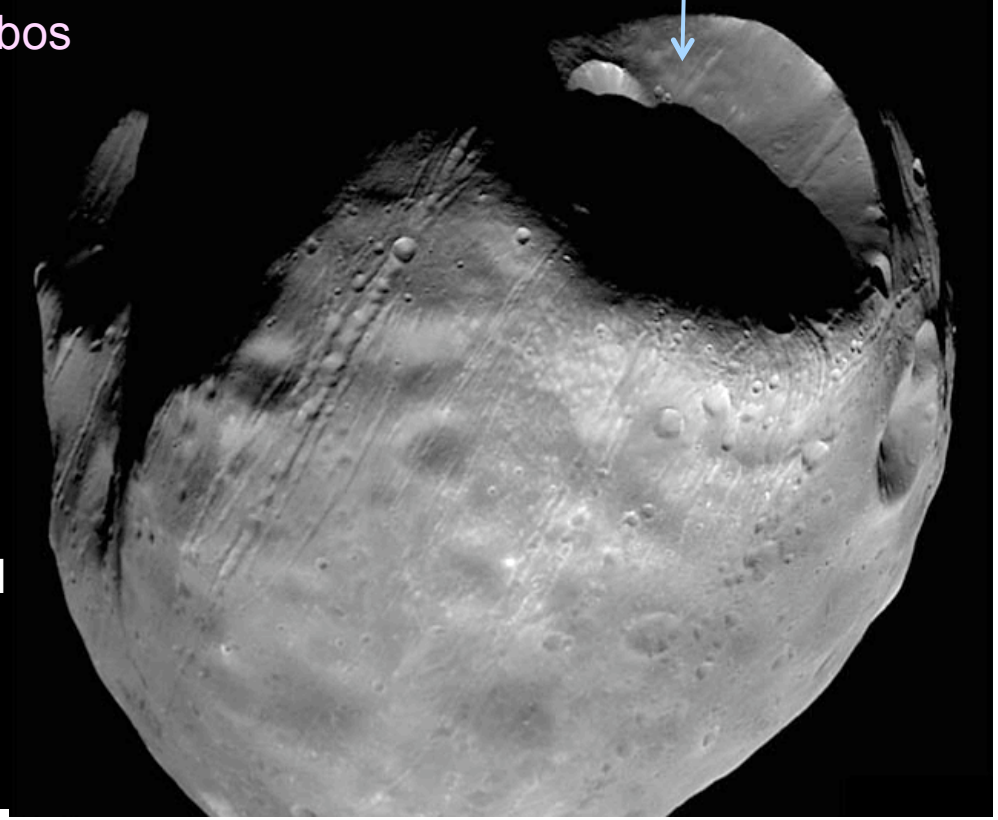
The Moons of Mars: Phobos

Phobos is similar to Deimos but a little bigger: 17 x 13 x 11 miles in diameter. Fracture grooves show that the collision that created the 6-mile crater Stickney almost shattered the entire moon.

Phobos is only 5627 miles (less than 3 Mars radii) from the center of Mars. Its orbital period of 7 h 39 min is 1/3 of a Martian day, so Phobos moves faster than the planet's rotation. It moves "backward" in the Martian sky, rising in the west and setting in the east.

Phobos is sinking toward Mars by 6 feet every 100 years. In 30 to 50 million yr, it will break up into a planetary ring or crash onto the surface of Mars.

The escape velocity is 25 mph. You could throw a baseball away from Phobos.



Asteroids

Asteroids form a belt or ring of rocks mostly between the orbits of Mars and Jupiter.

Sizes

The largest asteroid, Ceres, is ~ 1000 km in diameter. There are 15 asteroids known with diameters greater than 250 km and an estimated 100,000 with diameters greater than 1 km. By 2011, the number of asteroids known was > 550,000 (and growing).

Put together, all asteroids add up to less than 10 % the mass of the Moon.

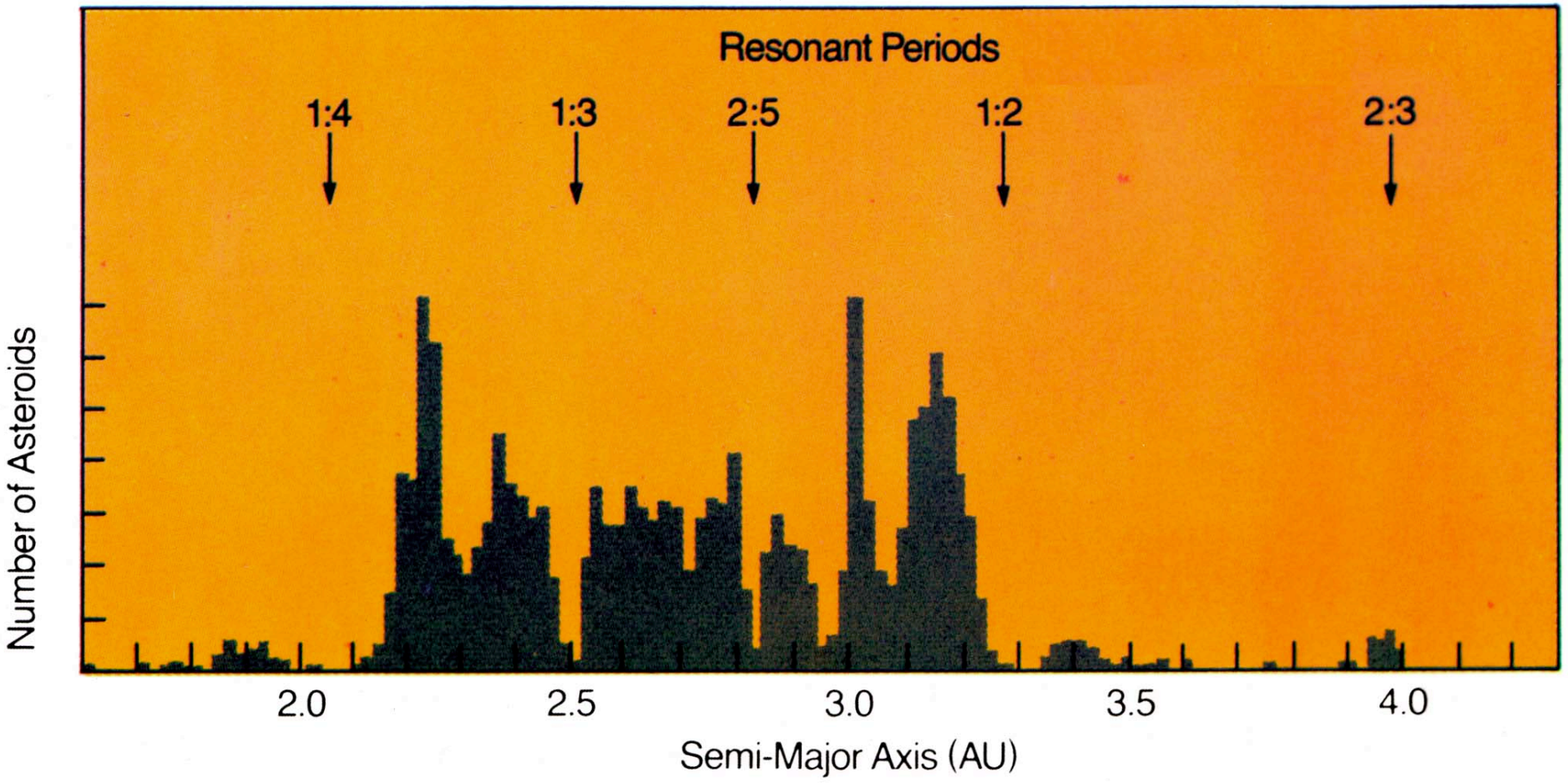
Orbits

Most asteroids have slightly elliptical orbits between Mars and Jupiter. Some parts of this “asteroid belt” are deficient in asteroids; these gaps are caused by resonances with Jupiter, just as gaps in Saturn’s rings are caused by resonances with its moons.

The asteroids Amor and Apollo have orbits that cross the orbits of Mars and Earth, respectively. Other asteroids (enough to be dangerous) do likewise.

We discussed the danger of asteroid impacts in the last lecture.

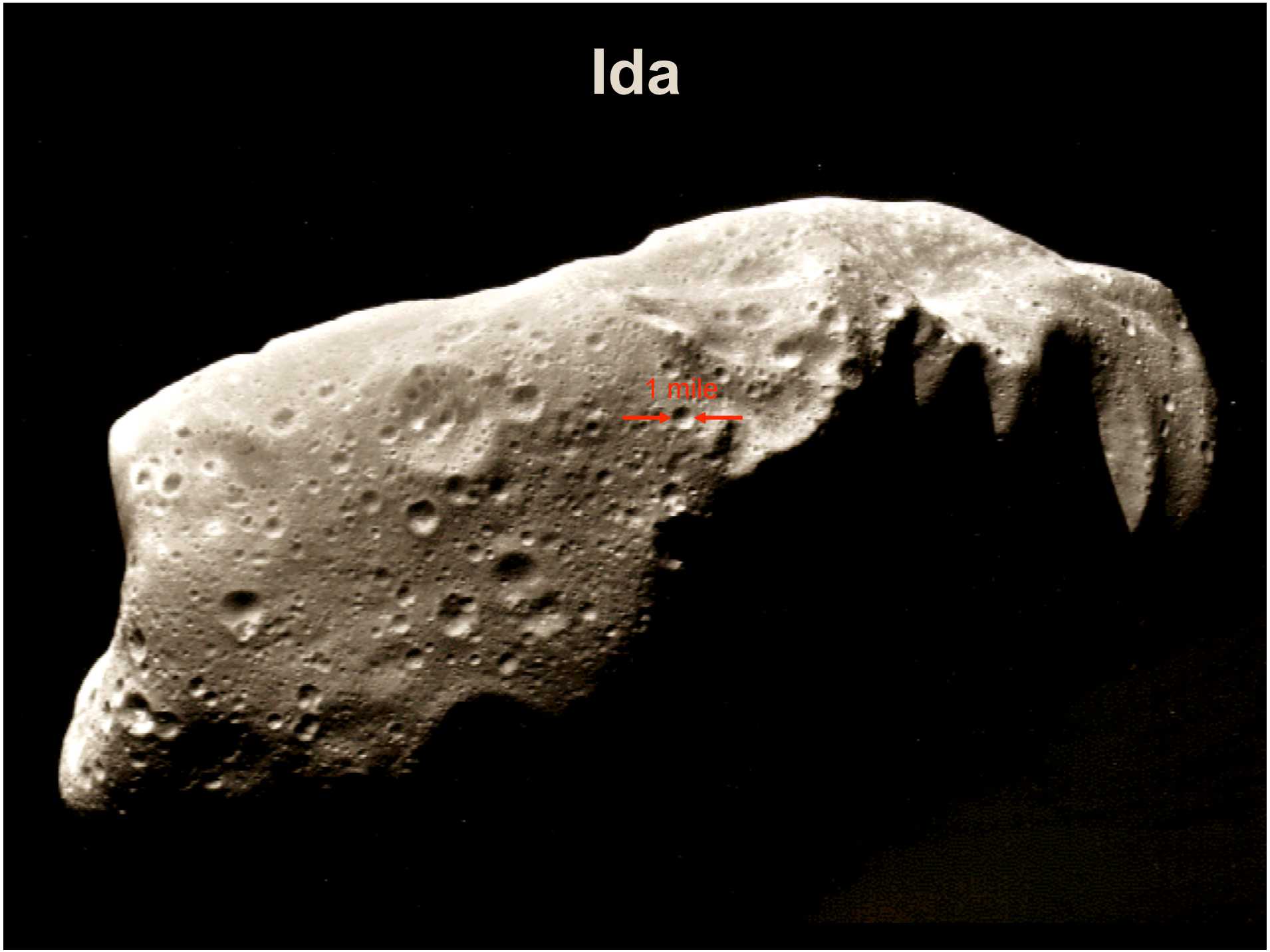
Resonances in the Asteroid Belt



Example — the 1:3 resonance: Period = (11.9 years / 3) = 4 years.

Semimajor axis $\bar{a} = \sqrt[3]{4^2} = 2.5$ AU

Ida

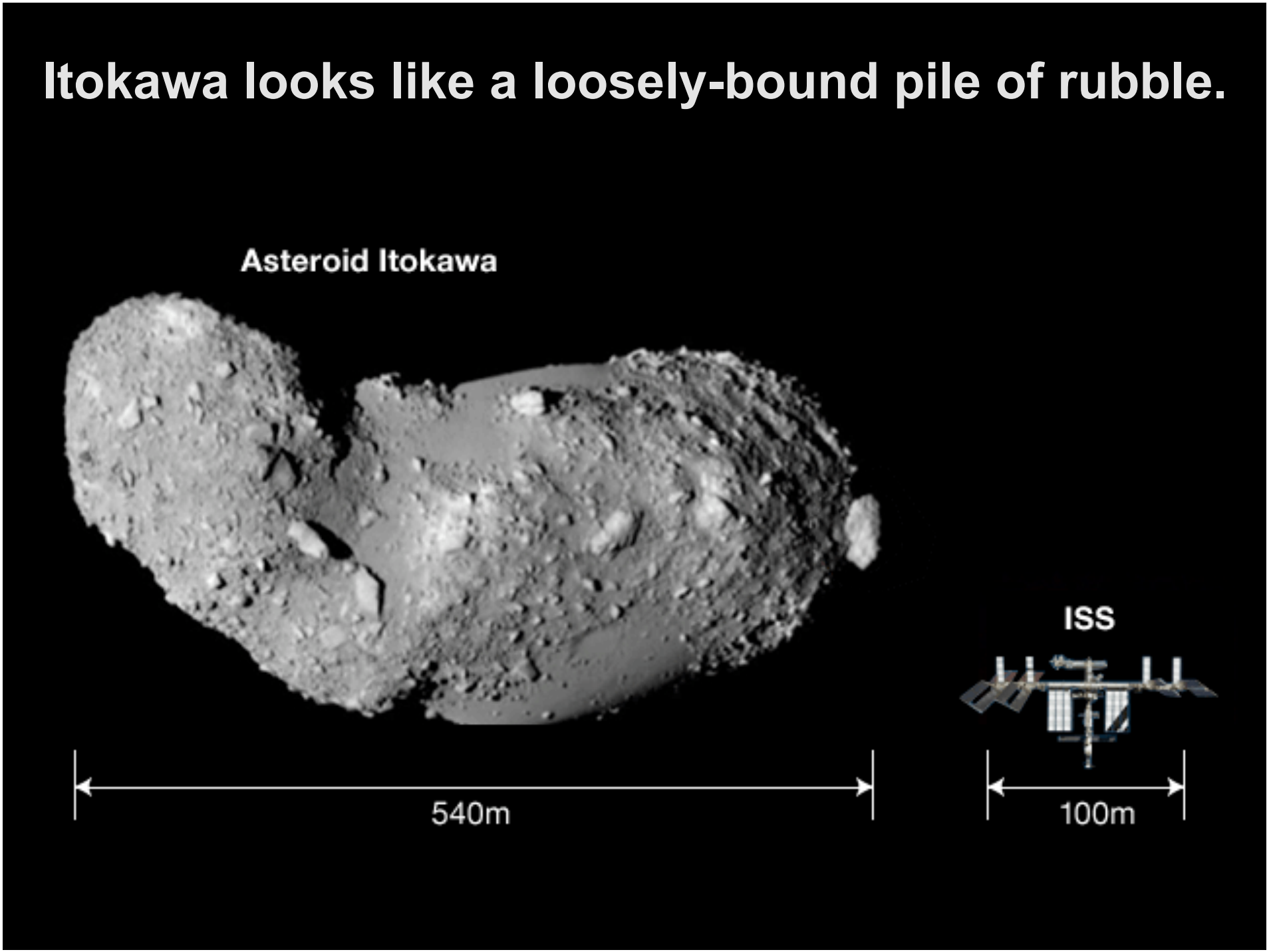


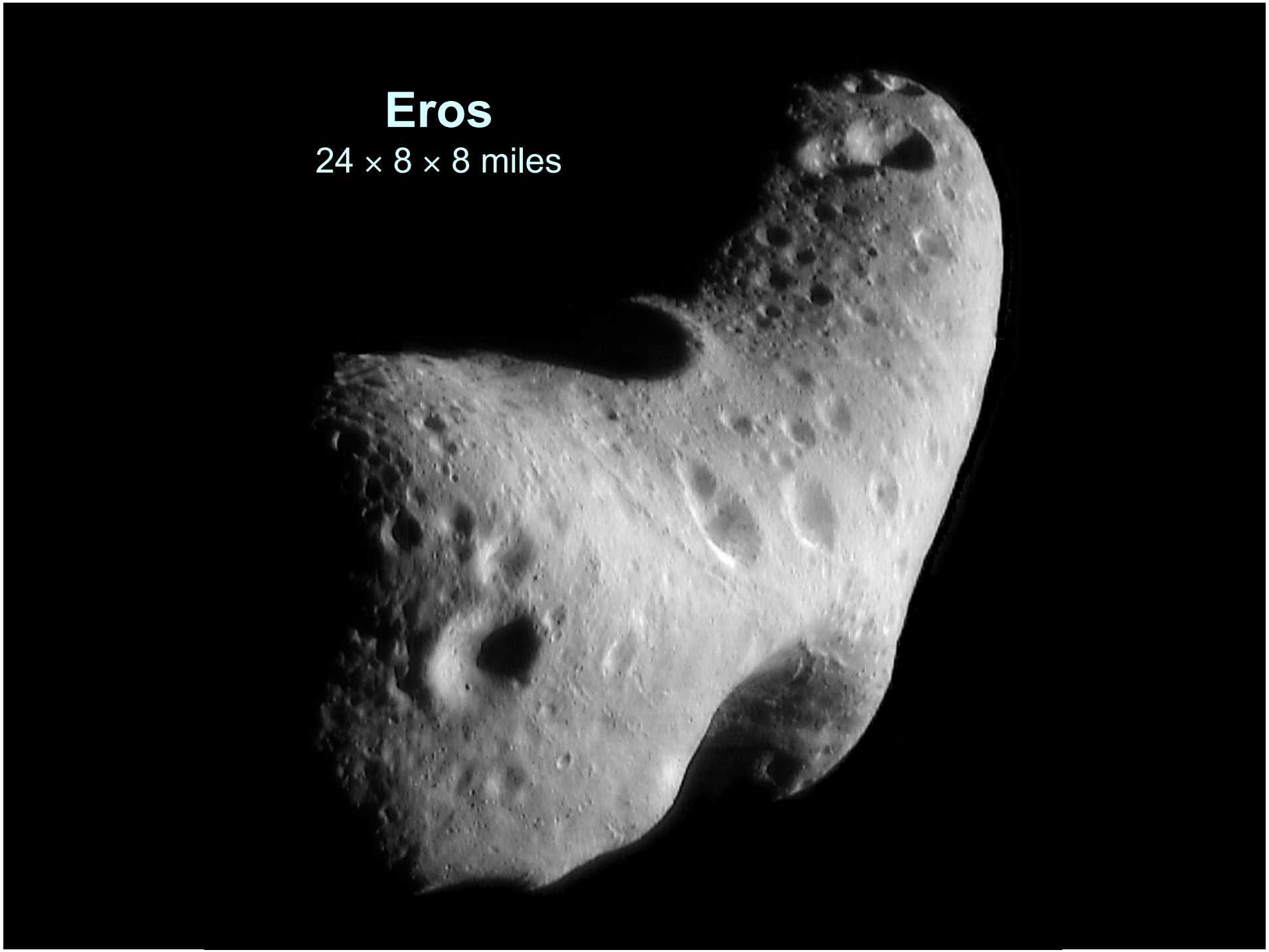
Ida

35 × 15 × 13 miles

Dactyl
(1 mile in diameter,
60 miles away from Ida)

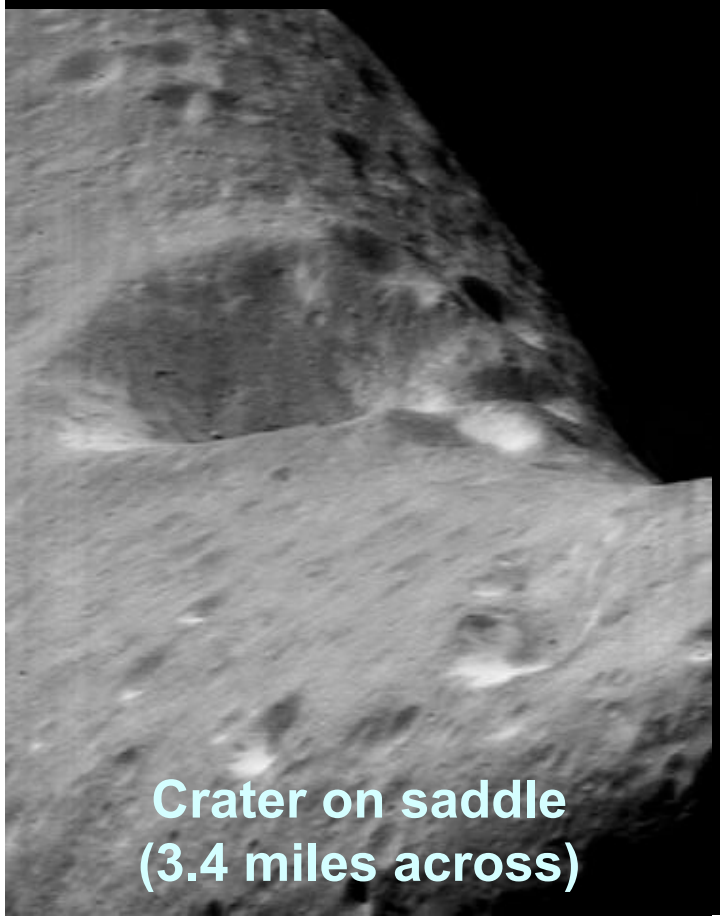
Itokawa looks like a loosely-bound pile of rubble.




Eros
24 × 8 × 8 miles

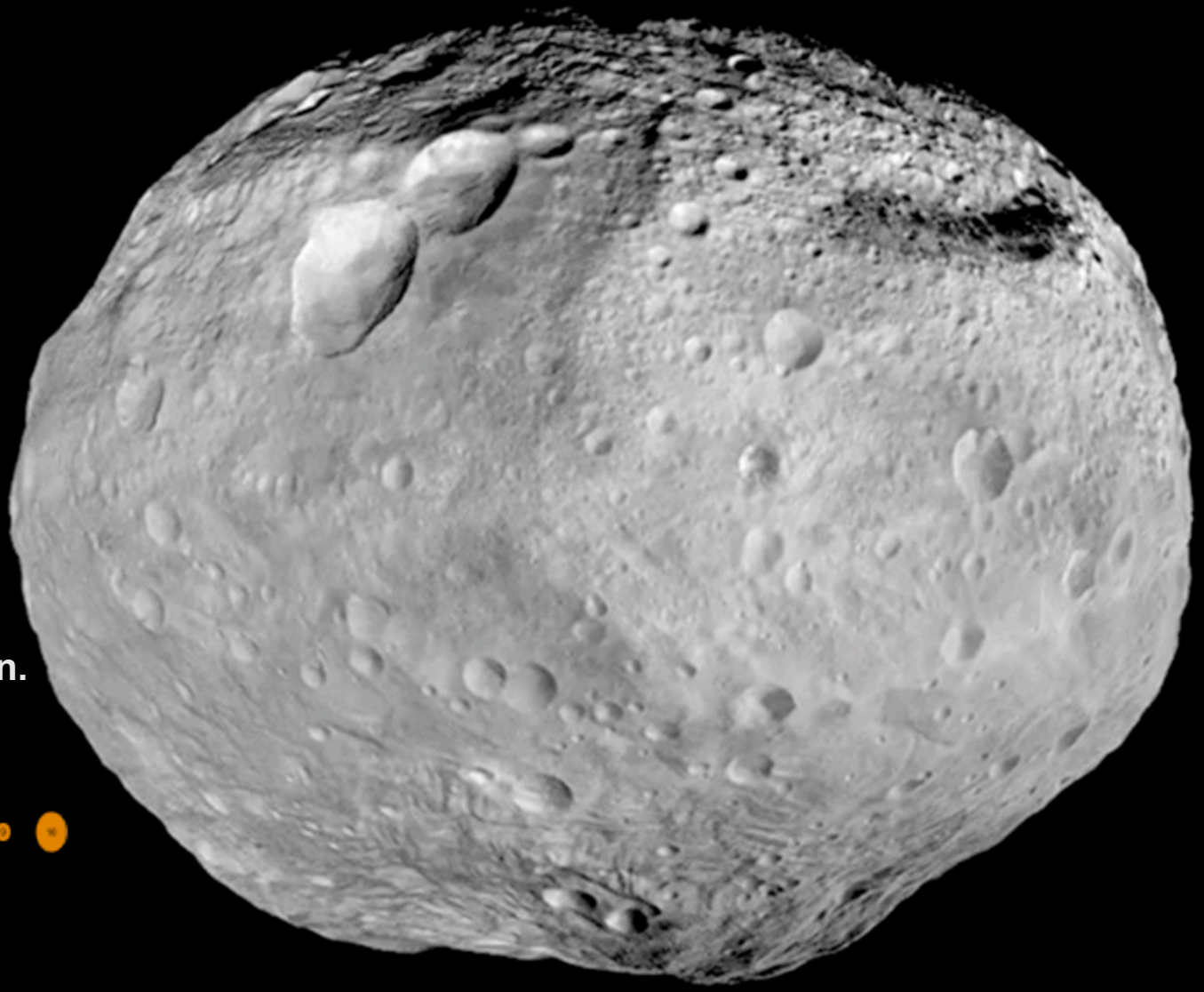
Eros

Closeup from 5 miles
Big boulder is 82 feet across.
(smallest rocks 7 feet)

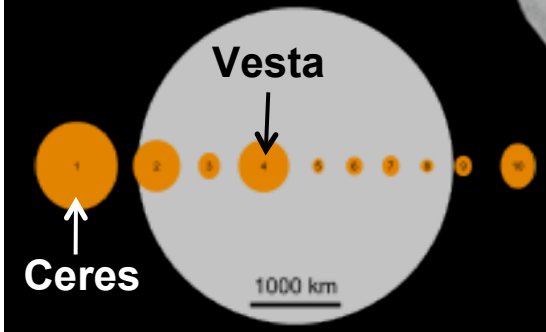


Crater on saddle
(3.4 miles across)

Vesta

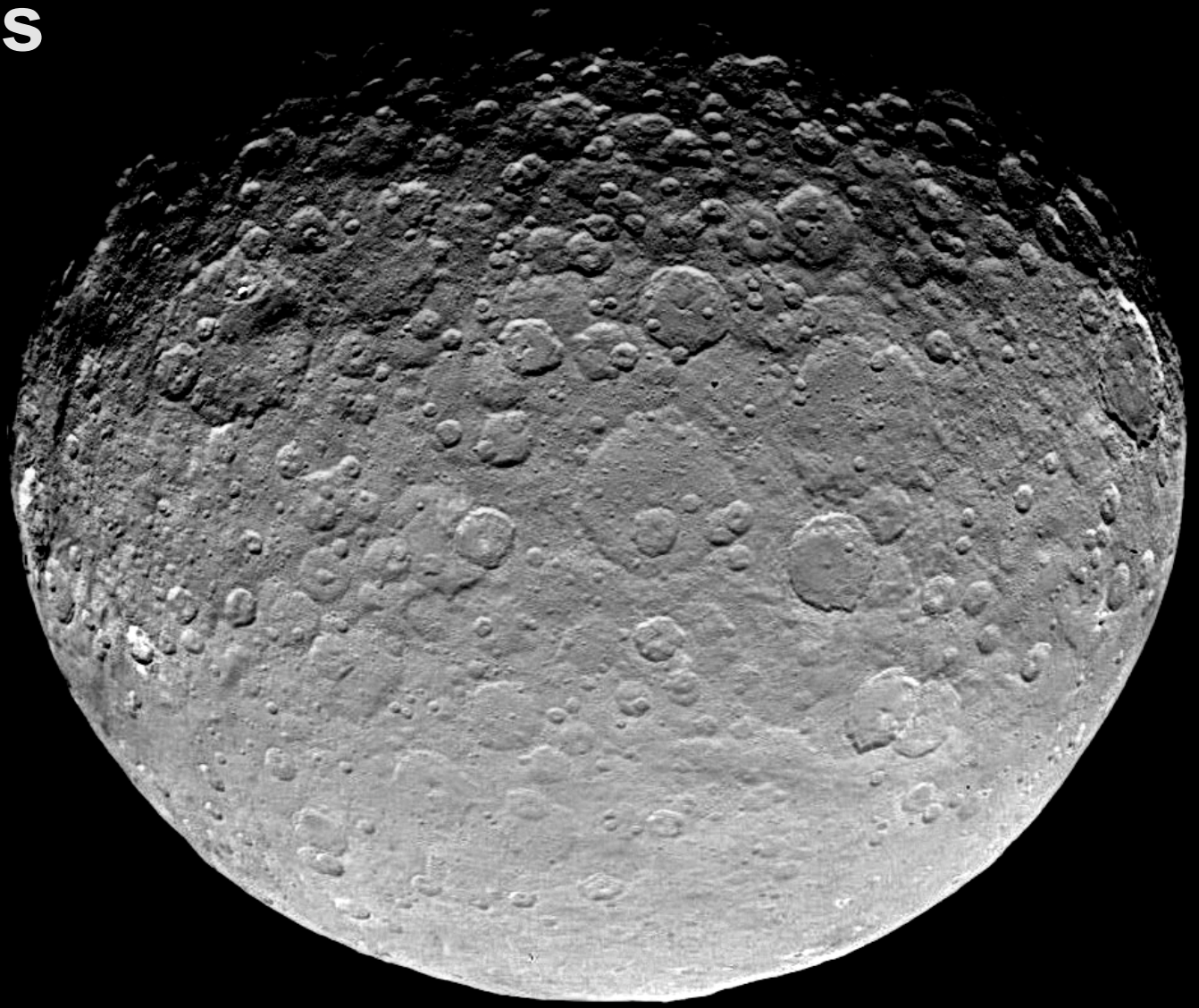


Biggest asteroids compared to the size of Earth's Moon.



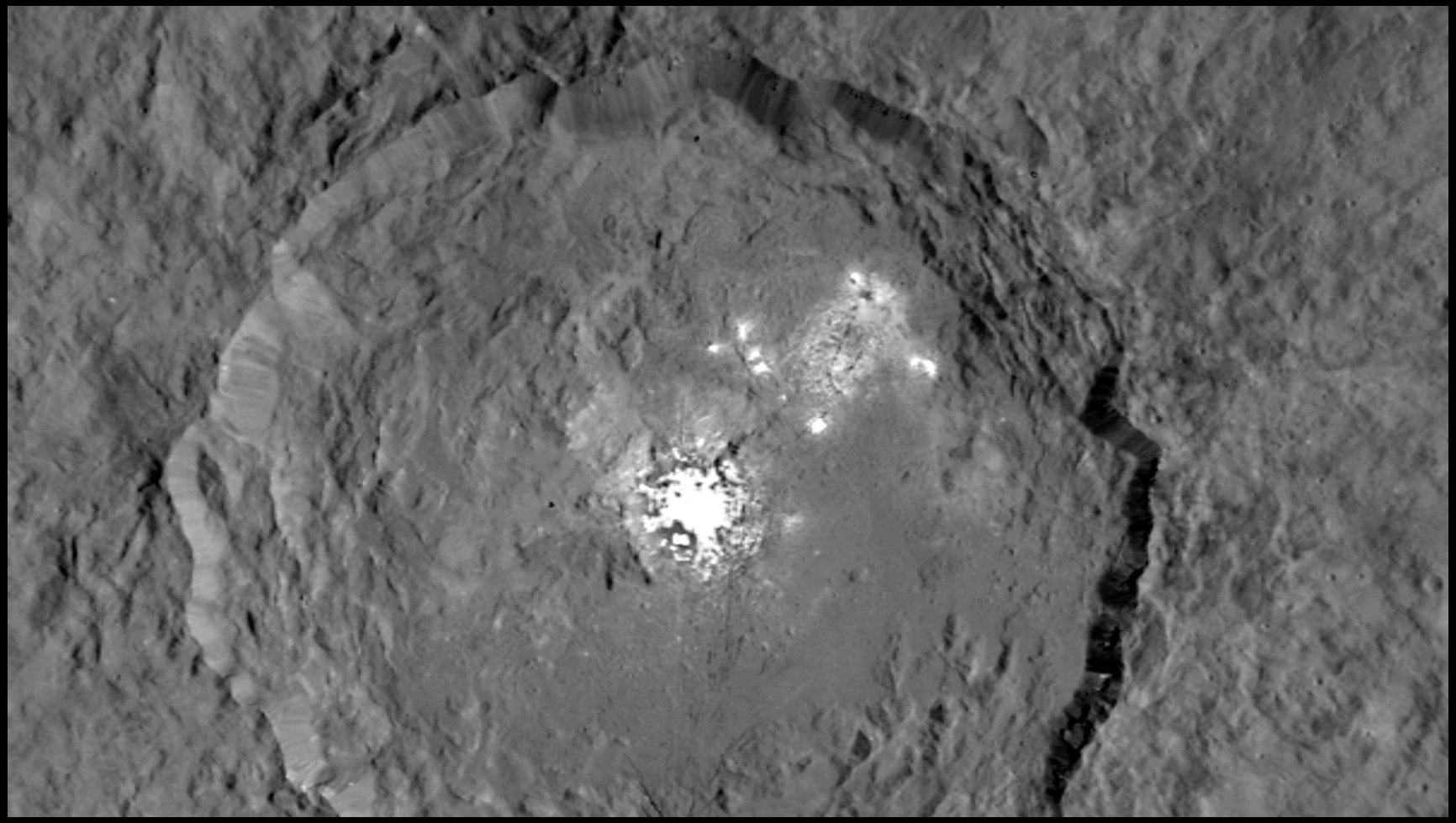
Vesta is the second-largest asteroid (344 x 334 x 268 miles).
The "Dawn" spacecraft orbited and studied it for 1 year in 2011/2012.
It is one of the smallest differentiated bodies in the Solar System, with a rock surface and iron-nickel core.

Ceres



Ceres is the biggest asteroid (587 miles diameter), the only one big enough to be spherical. The Dawn spacecraft is in orbit around it now. It is thought to have a rocky core and a water ice mantle.

Ceres: Occator crater and bright spots



Periodic haze above the bright spots suggest that they are at least partly made of water ice that vaporizes. They may also contain salts. So Ceres shares properties with rocky asteroids and icy Kuiper belt objects. Other asteroids outgas, too, sometimes.

The Not-Planets

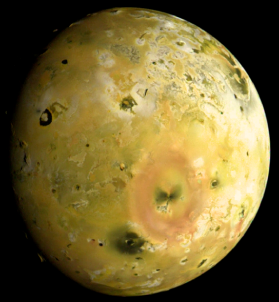
Many large round worlds are not currently classified as planets: the solar system's major moons, the largest asteroids, and large Kuiper belt objects. These are the ones spacecraft have visited.

Images from Galileo (Jupiter's moons), Cassini (Saturn's moons), Voyager 2 (Uranus and Neptune's moons). New Horizons (Pluto), Dawn (asteroids). Data from NASA/JPL/JHUAPL/SwRI/UCLA/MPS/DLR/IDA processed by Ted Stryk, Gordan Ugarkovic, Emily Lakdawalla, and Jason Perry. Earth's Moon photo by Gari Arrillaga. Montage by Emily Lakdawalla, The Planetary Society. blog@planetary.org.

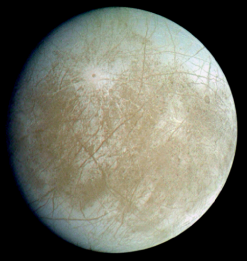
Earth's Moon:

The Moon

Jupiter satellites:

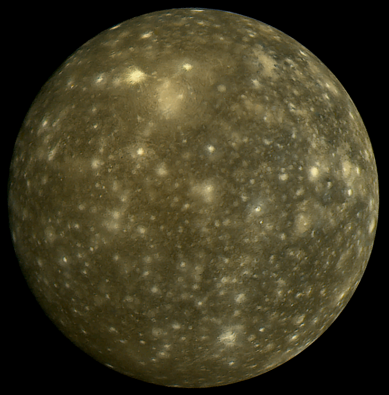


Io



Europa

Ganymede



Callisto

Saturn satellites:

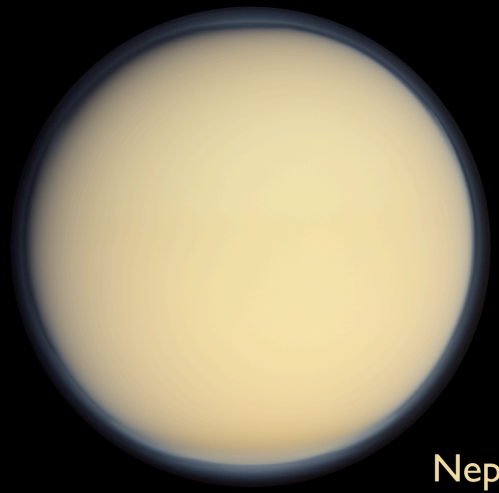
Mimas

Enceladus

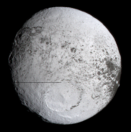
Tethys

Dione

Rhea



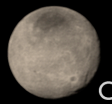
Titan



Iapetus

Pluto system:

Pluto



Charon

Asteroids:

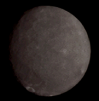
Vesta

Ceres

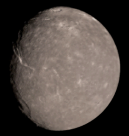
Uranus satellites:

Miranda

Ariel



Umbriel



Titania

Oberon

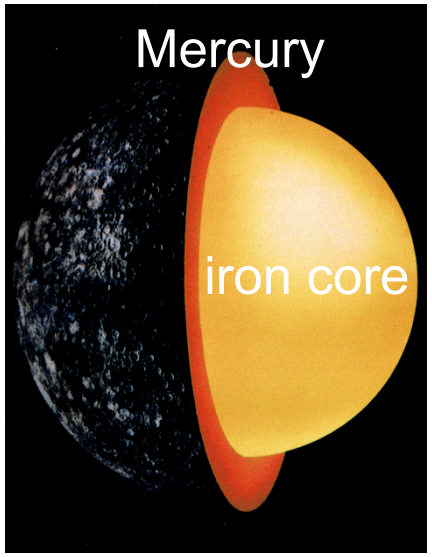
Neptune satellites:

Triton

Proteus

THE PLANETARY SOCIETY

The Moon and Mercury



Our Moon and Mercury are very similar. Both have very old surfaces that are heavily cratered. Our Moon is mostly made of rock. Mercury is a metal ball with a thin rock crust.

Neither shows tectonic activity – there is no continental drift.

Impact cratering

The lunar highlands are covered with craters mostly more than 4 billion years old. Mercury is less cratered — the bombardment was less intense near the Sun or the surface of Mercury solidified later than that of the Moon.

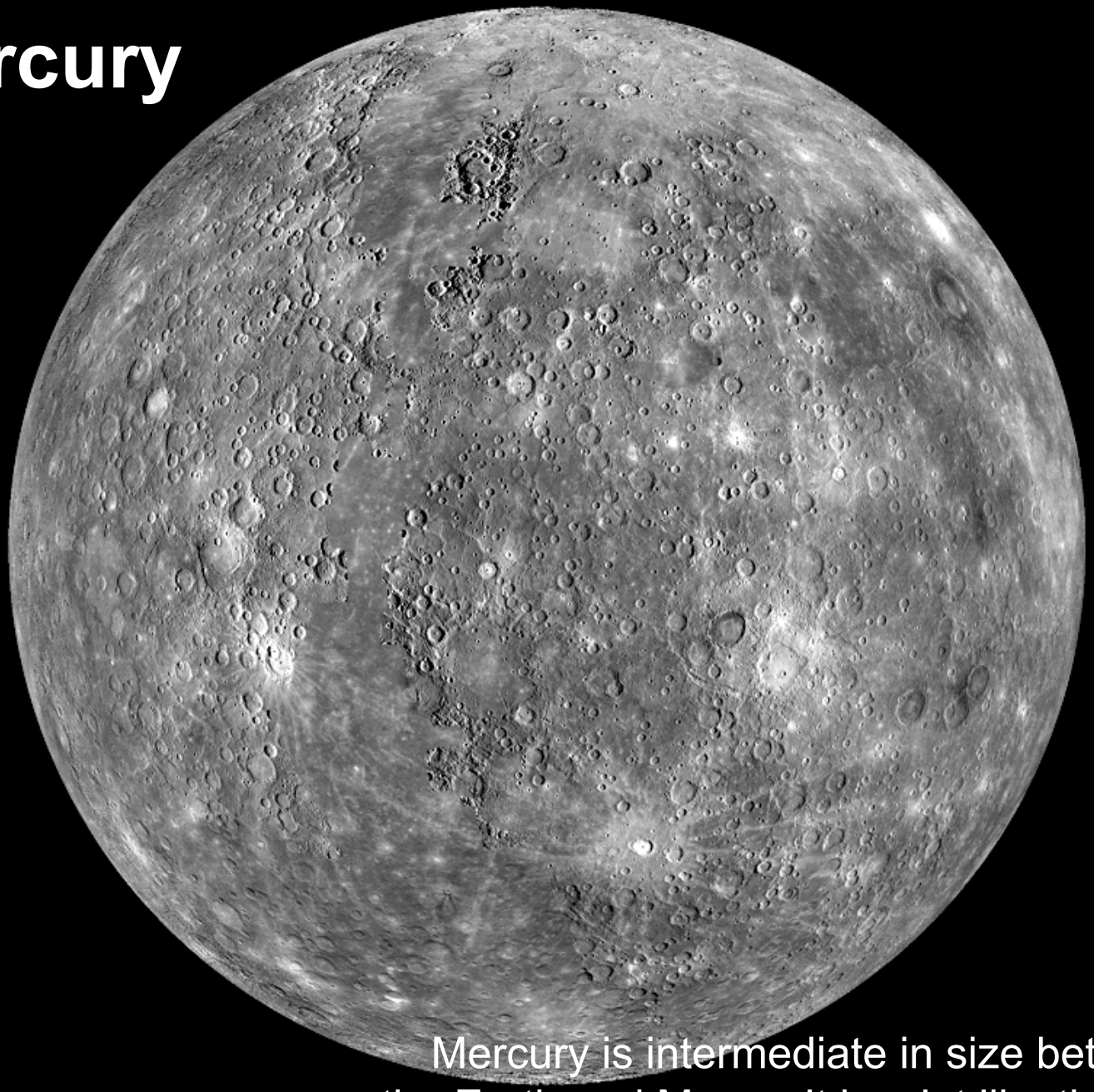
Impact basins

The largest impacts make enormous craters ringed by mountain chains. Typically, thy fill with lava, producing impact basins such as Orientale on the Moon and Caloris on Mercury.

Maria

Widespread lava flooding of low-lying plains and impact basins created the dark lunar maria or “seas”. These regions are found only on the near side of the Moon and are 3 to 4 billion years old.

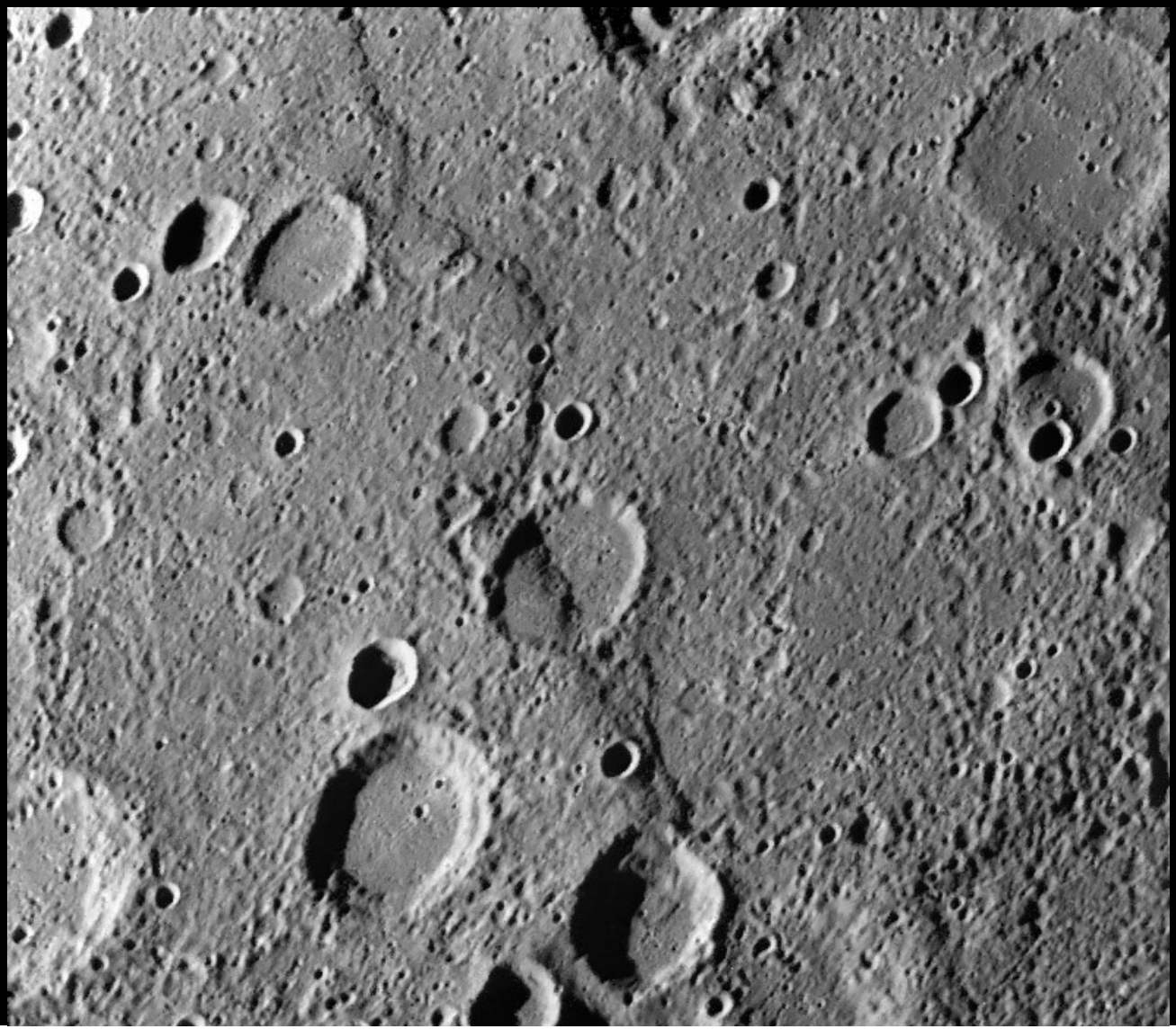
Mercury

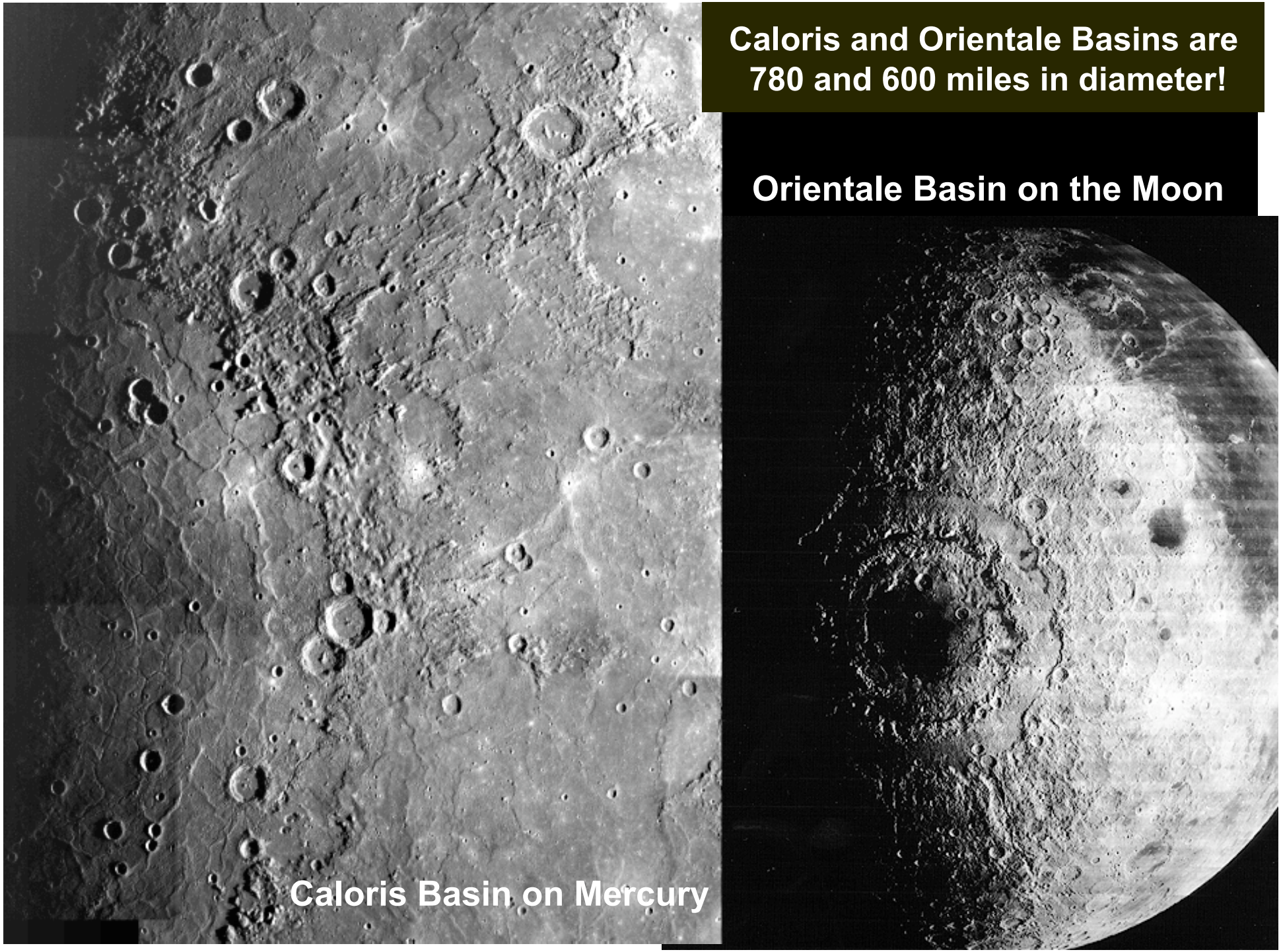


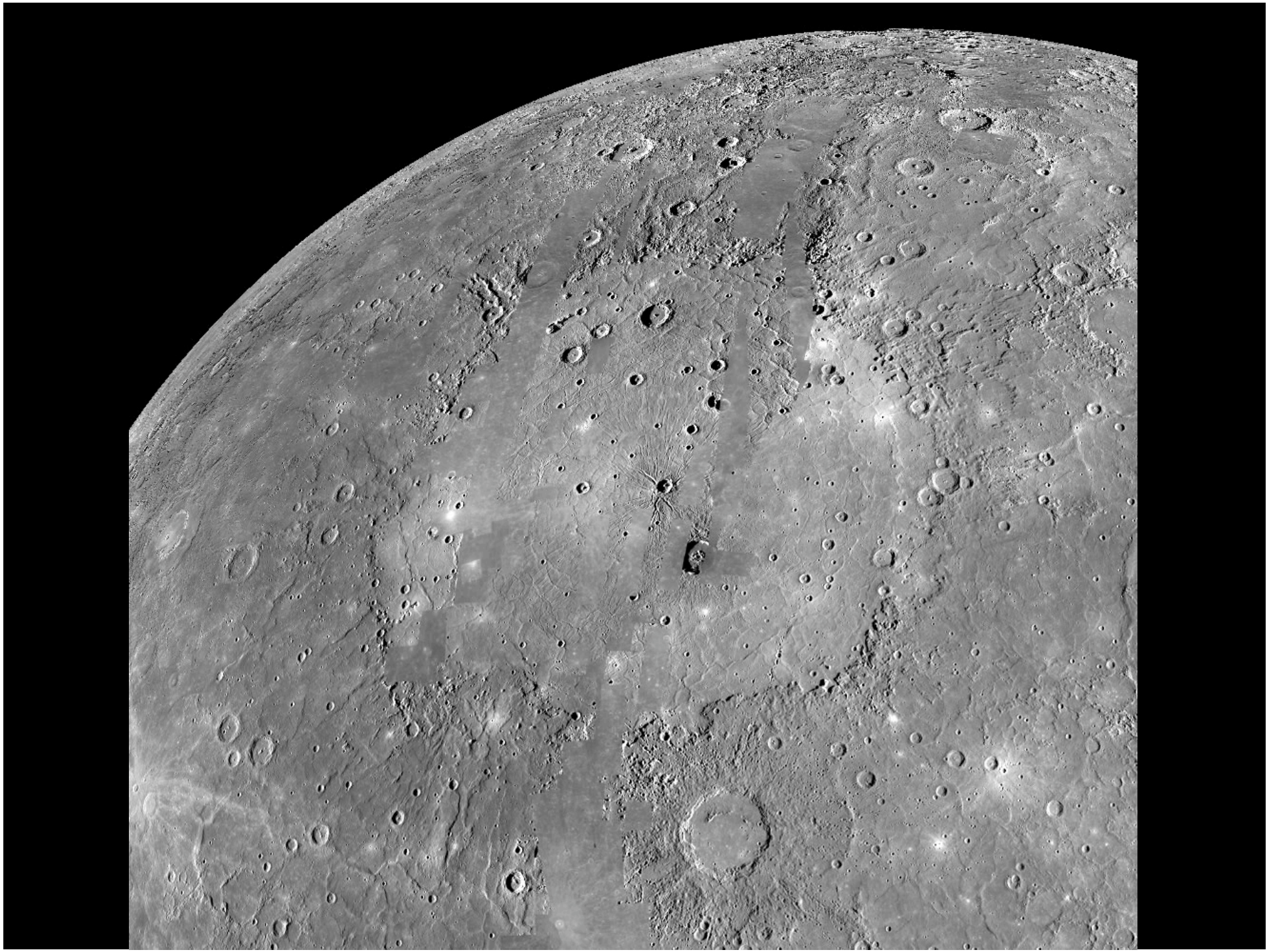
Mercury is intermediate in size between the Earth and Moon. It is a lot like the Moon.

Mercury

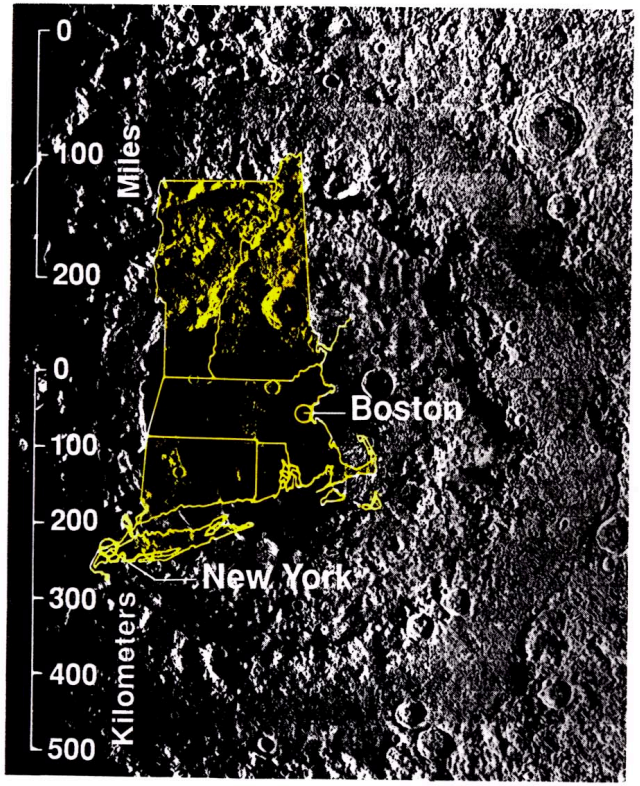
Lobate scarps are wrinkles caused by the shrinking of the planet as it cooled.

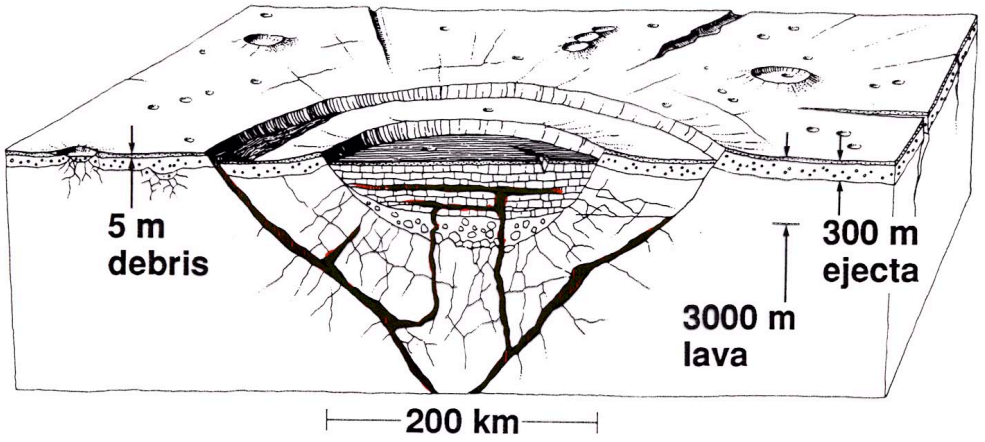



Caloris and Orientale Basins are 780 and 600 miles in diameter!
Orientale Basin on the Moon
Caloris Basin on Mercury

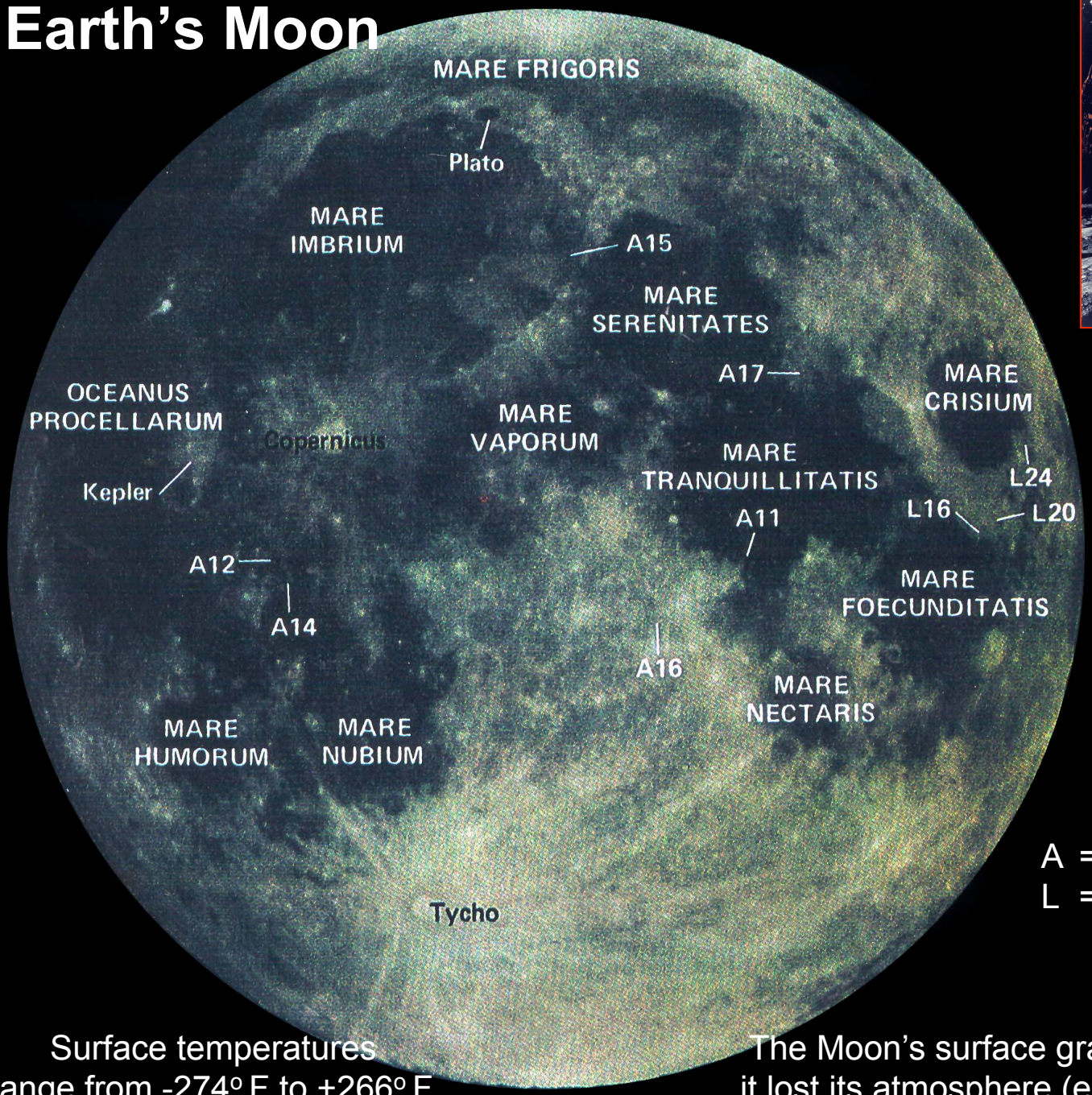


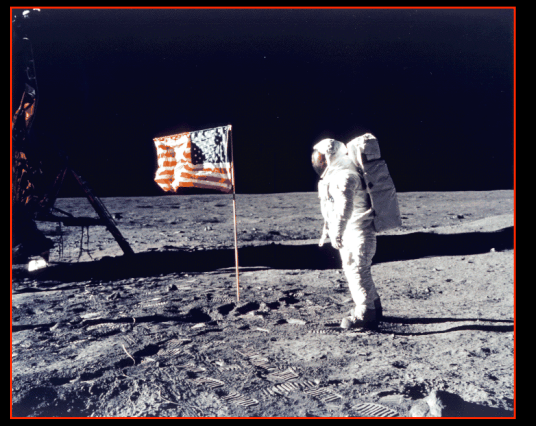
Caloris Basin on Mercury





Earth's Moon



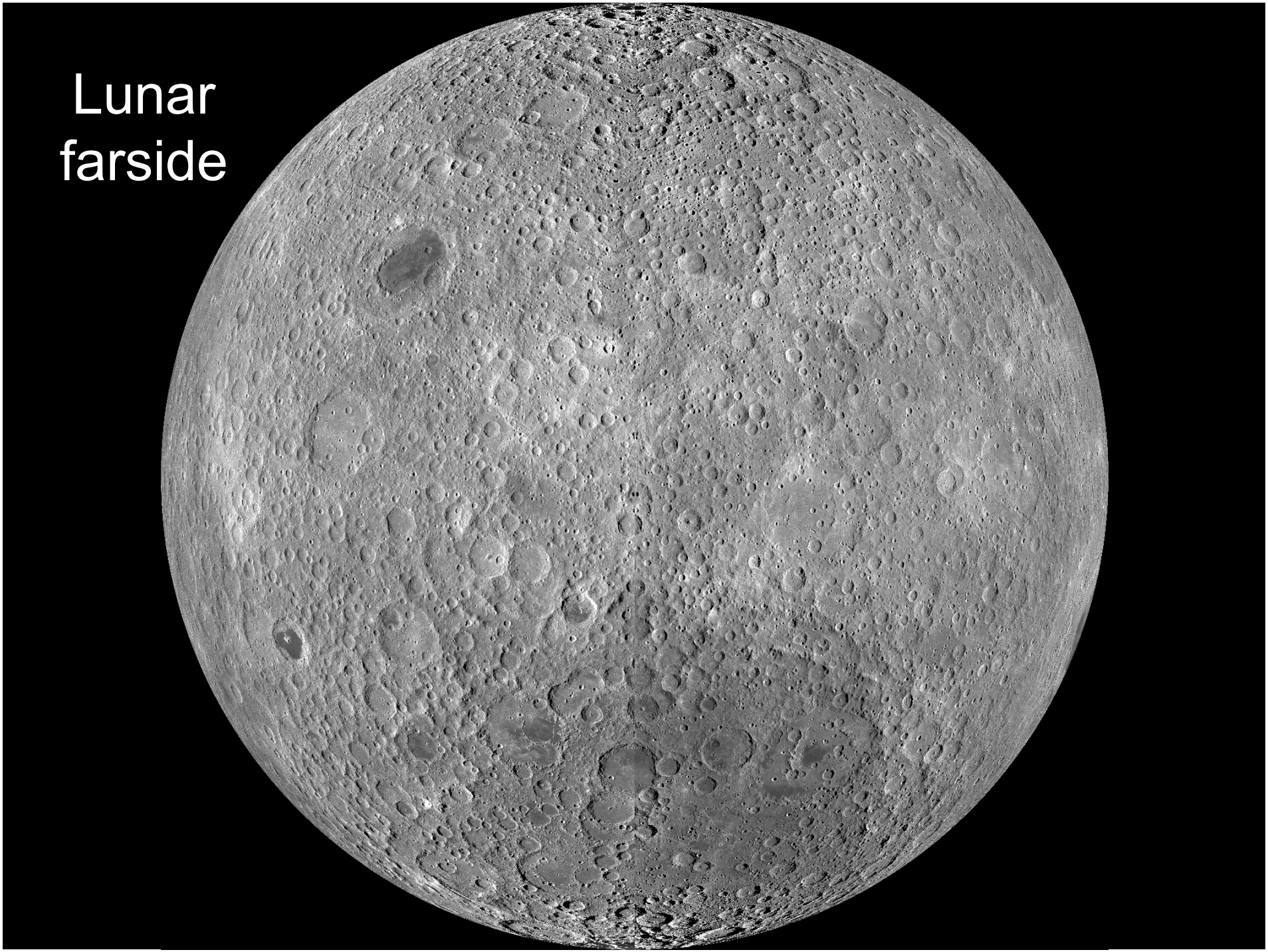


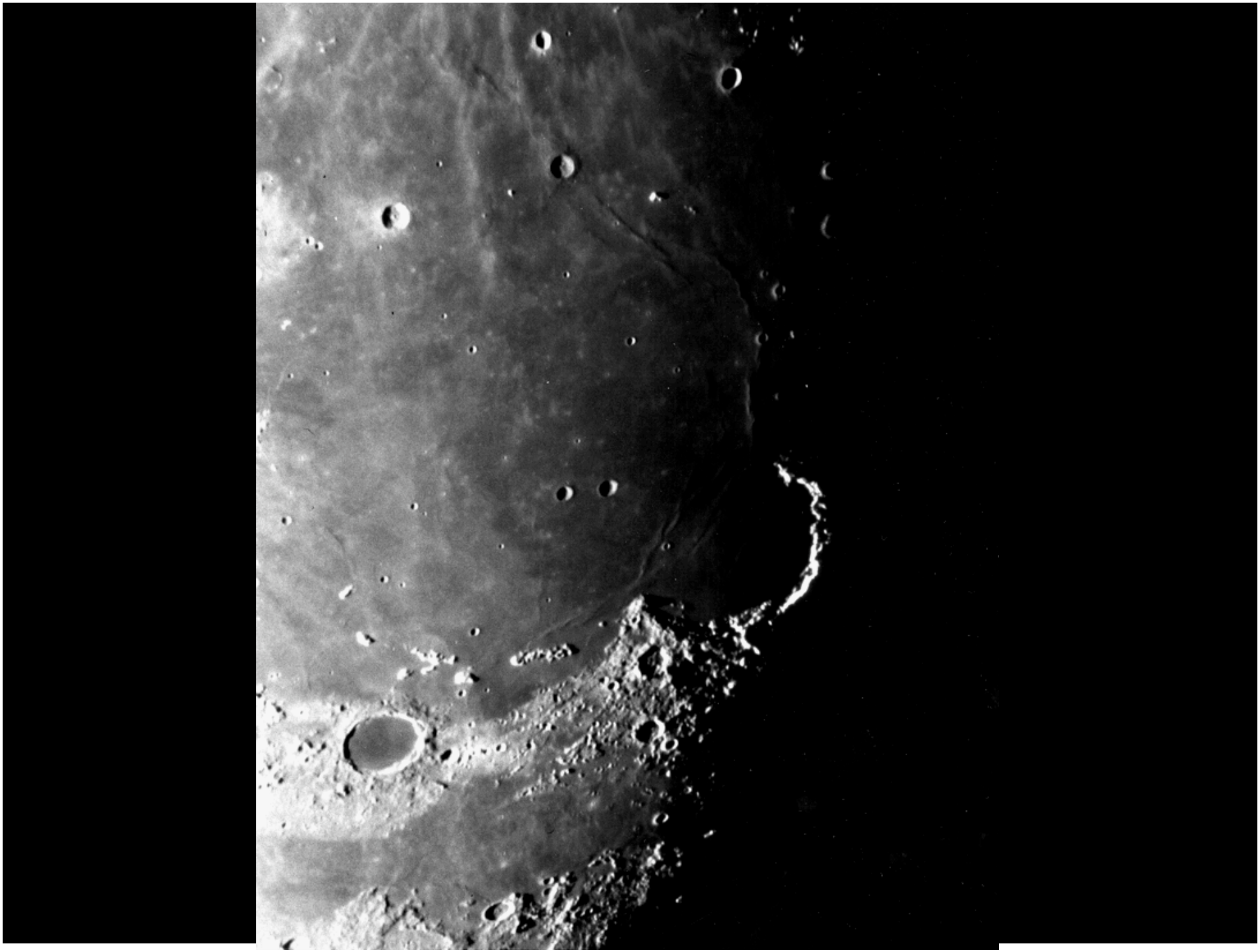
A = Apollo landing site
L = Soviet Luna mission that returned rocks to Earth

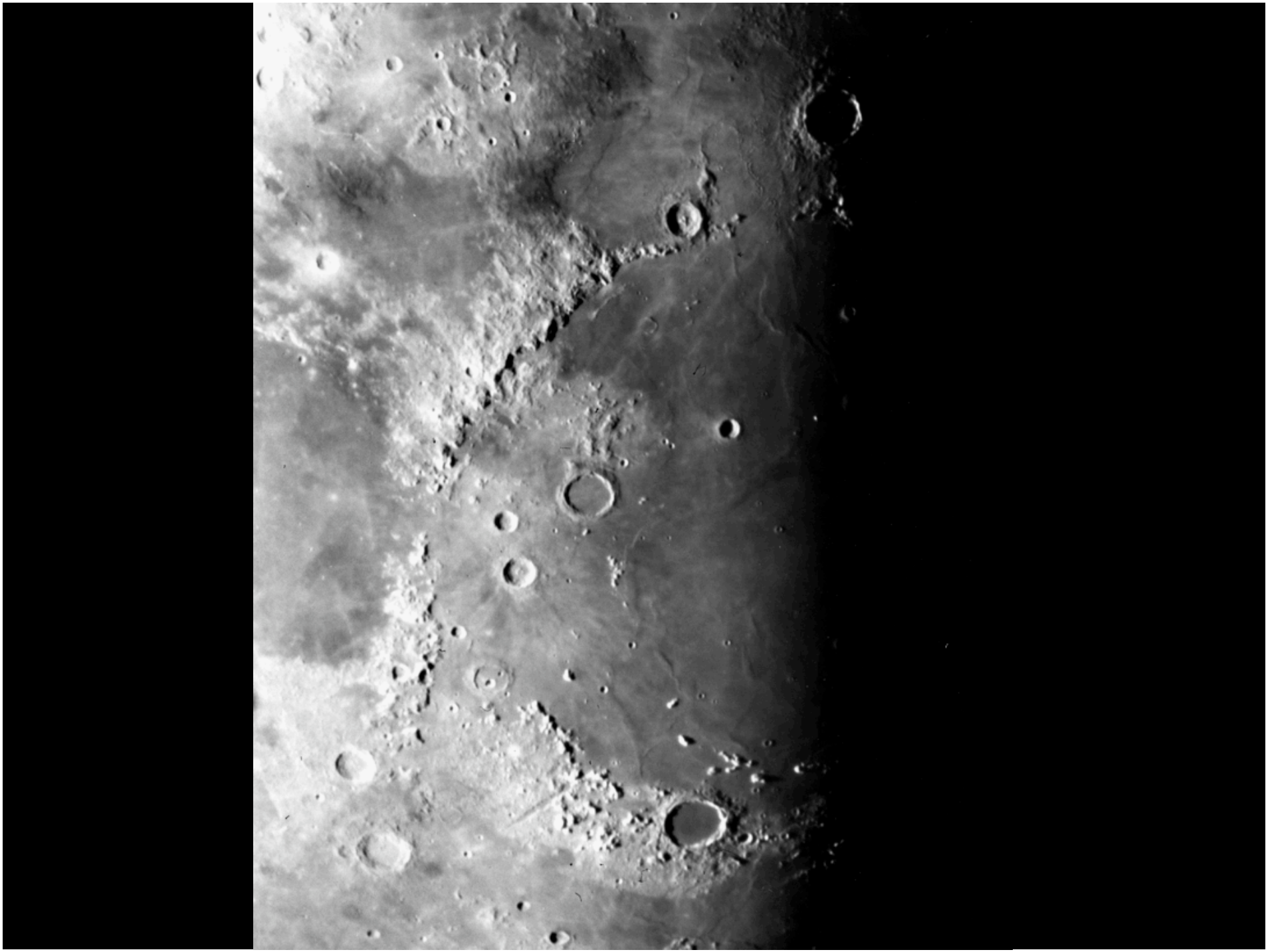
Surface temperatures range from -274° F to +266° F.

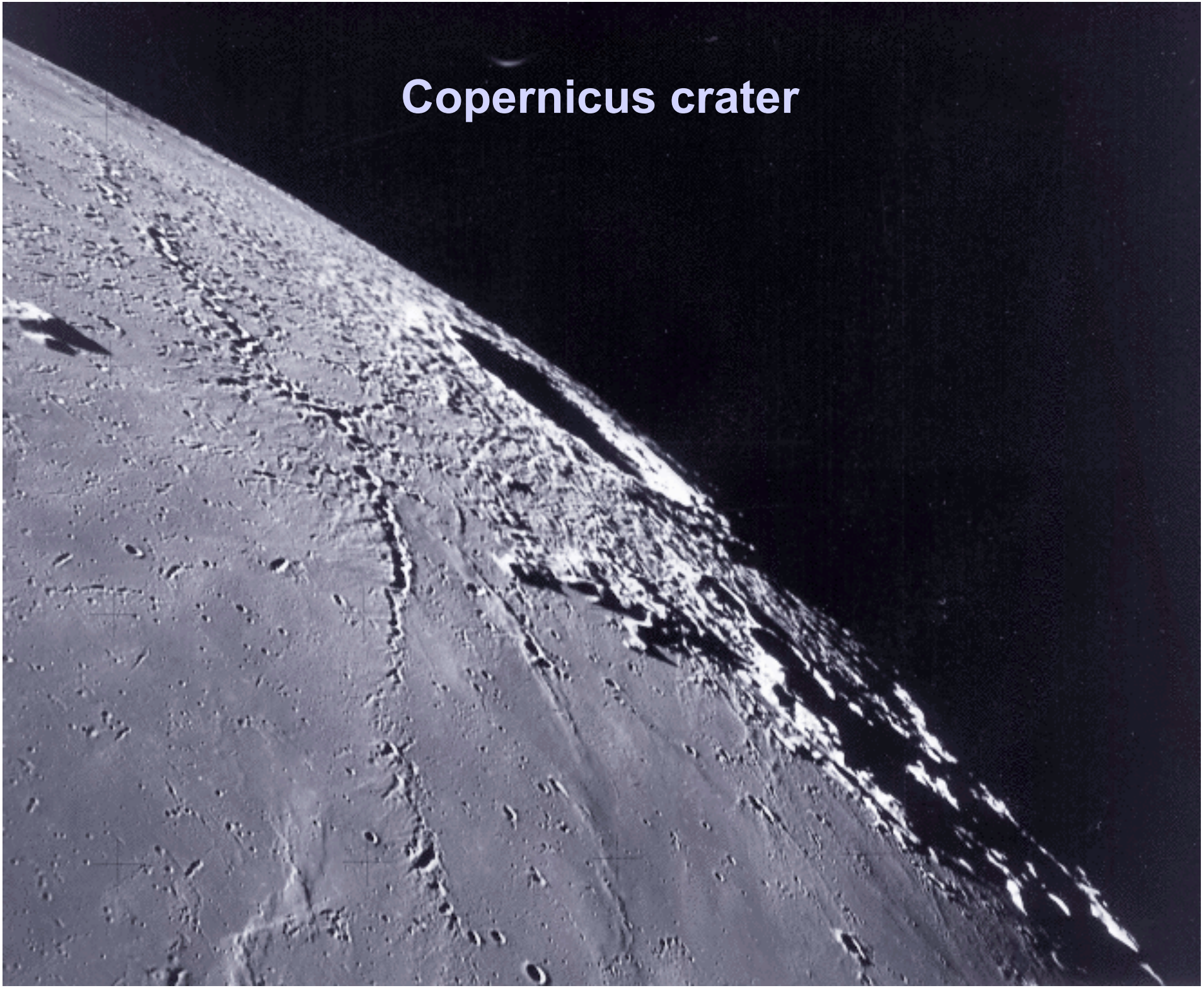
The Moon's surface gravity is ~ 1/6 of Earth's, so it lost its atmosphere (escape velocity ~ 2.4 km/s).


Only the Earth-facing side
of the Moon has maria.
The crust is thinner there,
maybe because of tidal effects.
Lava flooded
big impact basins
only on the
near side.


Lunar
farside

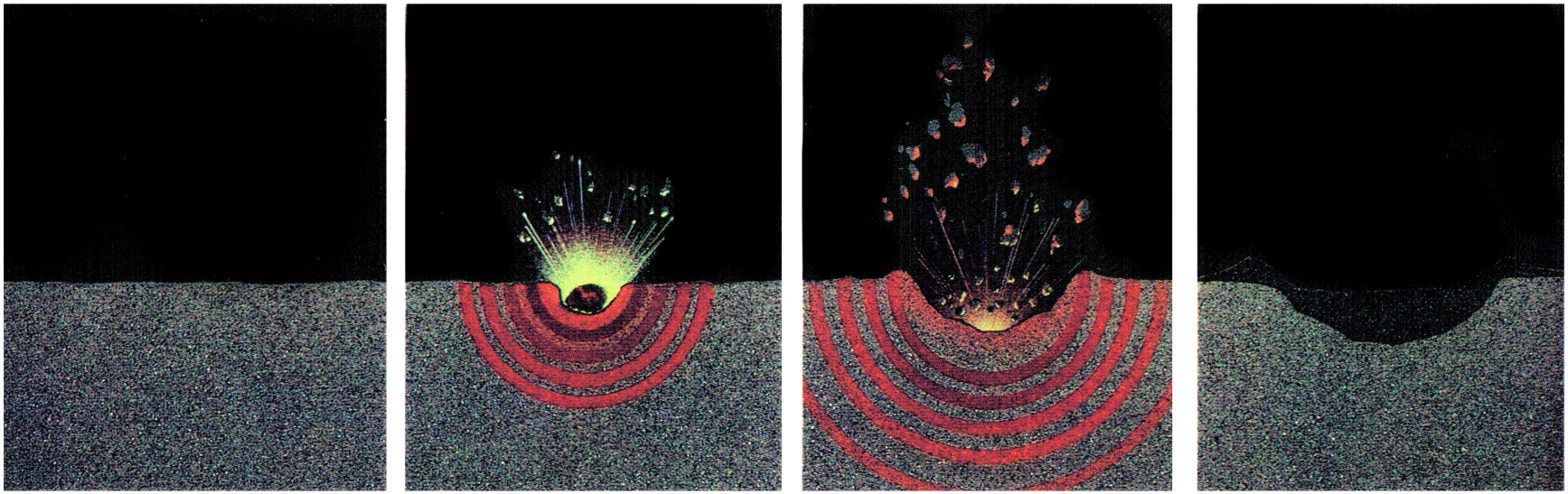





Copernicus crater

Impacts on the Moon now

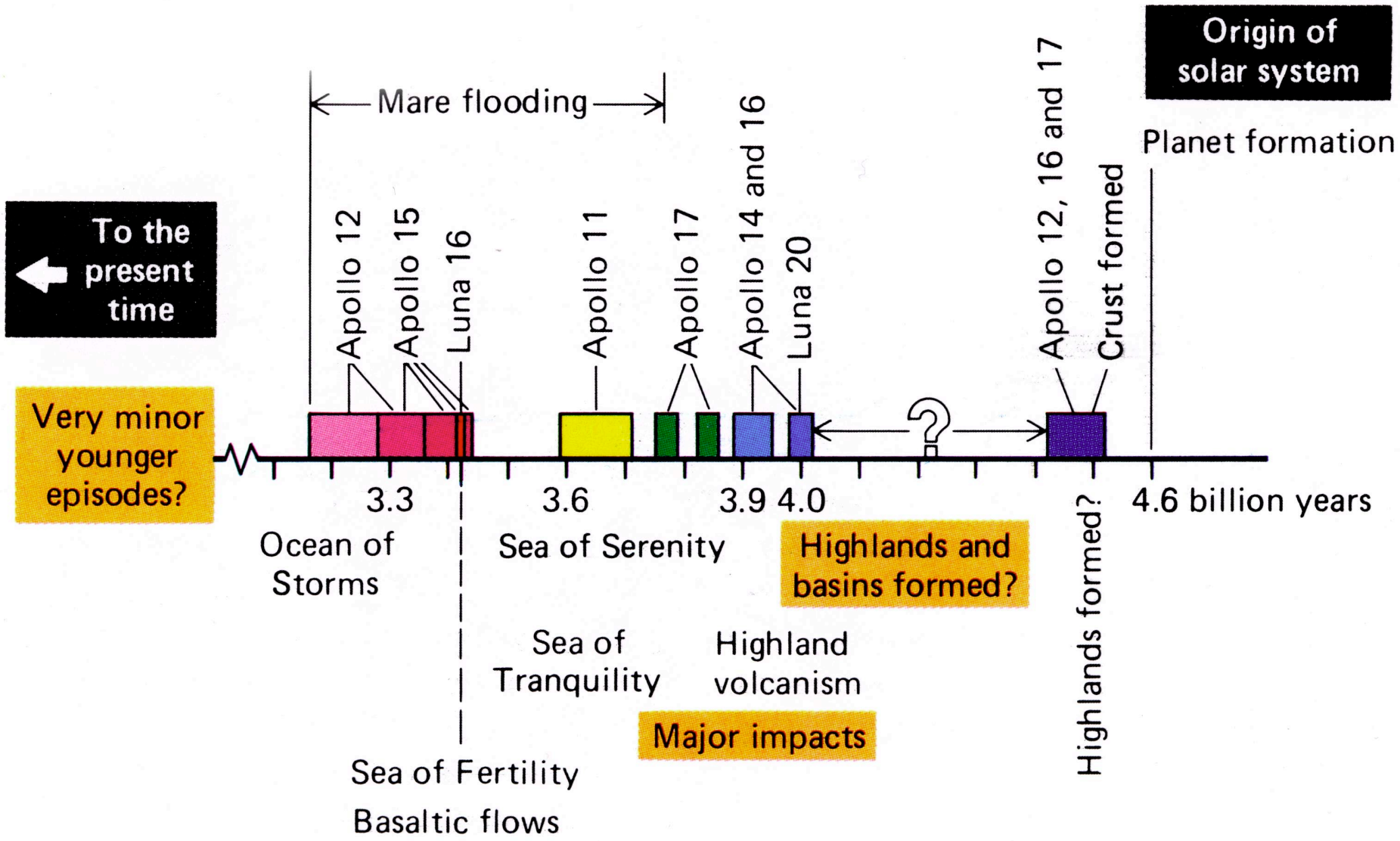
Get 1 new 10 km diameter crater every 10 million years
1 m month
1 cm few minutes



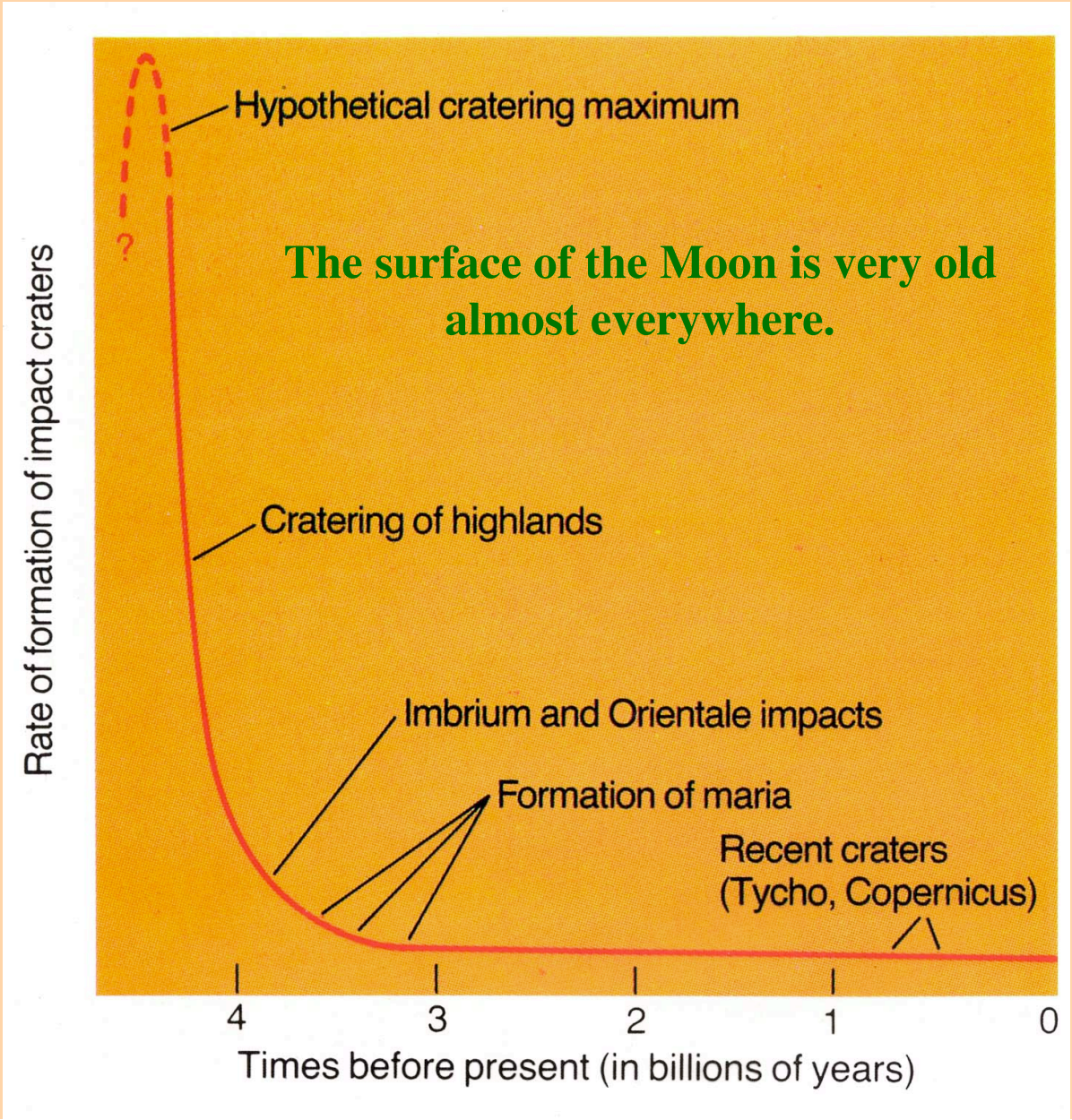
Micrometeorite erosion rate ≈ 1 cm per 2 million years

⇒ Astronaut footprints will last several million years.

Ages of Rocks Collect on 5 Apollo and 3 Luna Missions



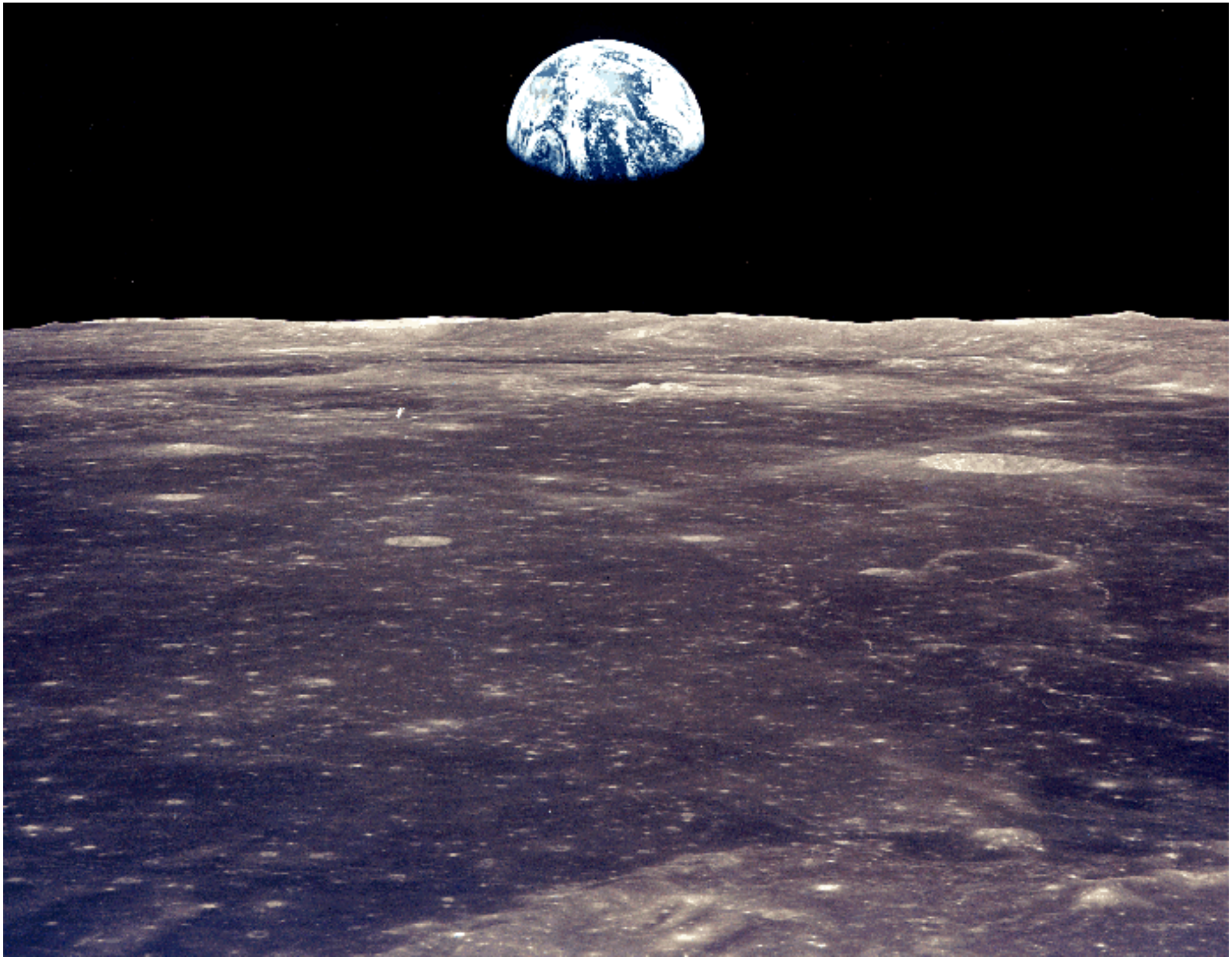
Cratering Rate on the Moon



I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth.

John F. Kennedy
May 25, 1961

John F. Kennedy
September 12, 1962



Apollo 11 landing: July 20, 1969

Apollo 11 — First Step on the Moon

Apollo 17: Last takeoff from the Moon
December 14, 1972

Rings of Jupiter, Saturn, Uranus, and Neptune Summary

Each giant planet has rings interior to the orbits of its biggest satellites.

Planetary rings are made of billions of tiny moonlets ranging in size from dust size to house size. Each orbits its planet in its own circular orbit. Ring particles that are closer to the planet revolve around it faster. So the rings never rotate like solid bodies.

Gaps in the rings are due to the gravitational effects of the bigger satellites. For example, the Cassini division in Saturn's rings is created by the 2:1 orbital resonance with the innermost big moon, Mimas. A particle that orbits in the Cassini division would circle Saturn twice for every one orbit of Mimas. Therefore Mimas lines up in the same way with the planet and the ring particle during every other orbit. Therefore it repeatedly pulls on the particle in the same direction. This perturbs the particle out of its resonant orbit until it hits another ring particle. In this way, Mimas has cleared out the ring particles that used to be in the Cassini division. Other, more minor, ring gaps are similar.

Planetary rings do not last long (for example) because of collisions between ring particles. The rings of Saturn are relatively young, probably only several 10s of millions of years old. The rings of Jupiter, Uranus, and Neptune are much older. The observation that all four Jovian planets have rings that are much younger than the age of the Solar System suggests that they reform many times. Probably rings are formed as a result of collisions of moons with each other and with asteroids and comets.

Satellites of Jupiter, Saturn, Uranus, and Neptune Summary

Each giant planet has at least 8 — dozens of known moons. They are Solar Systems in miniature.

Satellites range in diameter from 5280 km down to tens of km and probably less. Satellites smaller than ~100 km are non-spherical because their surface gravities are too weak to affect their shapes.

Jupiter's satellites Io, Europa, Ganymede, and Callisto; Saturn's satellite Titan; and Neptune's satellite Triton are substantially as large as Earth's Moon or larger. Ganymede, Titan, and Callisto are larger than Mercury. If these satellites were in orbit around the Sun, we would not hesitate to call them planets.

Most of the satellites larger than 100 km diameter are only partly rock: they contain large amounts of water ice. Many have densities only a little bigger than 1 g cm^{-3}. These are mostly ice.

Many show cracks and other evidence of straining. Uranus's satellite Miranda has broken apart and reformed, perhaps several times.

Satellites that have not been resurfaced are heavily cratered. Water ice is like rock at these low temperatures ($T < 100$ K), so impact craters form just like on the Moon and last for a long time.

Io is the most volcanically active body in the Solar System. Voyager 1 showed 8 vents active at once; they spew sulfur-rich lava as much as several hundred km. All of Io has been resurfaced many times. The energy source is tidal pumping by Jupiter. Io's orbit is elliptical, so tidal forces from Jupiter vary with orbital radius and periodically stretch the satellite. This produces energy equivalent to 2000 tons of TNT exploding every sec.

Europa may have a global ocean of liquid water under a thin ice crust. In places, the crust has broken and rafts of ice have moved around and refrozen in place. Again, the energy source to keep the interior warm is tidal heating by Jupiter. If Europa has interior oceans, it is one of the best places in the Solar System to look for life.

Saturn's satellite Titan has an opaque nitrogen-argon-hydrocarbon atmosphere. The surface pressure is 1.6 Earth atmospheres and the surface temperature is 94 K = -180^{o} C. This is just about the correct temperature and pressure to allow Titan have episodic ethane rivers, lakes, and seas.

Asteroids and the Moons of Mars
Summary

Asteroids are rock or rock+iron worlds orbiting the Sun in the inner Solar System. Most are in a ring called the "asteroid belt" between the orbits of Mars and Jupiter. The largest, Ceres, is ~ 1000 km diameter. Smaller asteroids are more numerous. All together, asteroids add up to less than 10 % of the mass of our Moon.

The asteroids in the asteroid belt are thought to be planetesimals and planetesimal fragments that never managed to get together to make a planet. Gravitational perturbations from Jupiter are the probable reason. Gaps in the asteroid belt are like gaps in planetary ring systems: they are caused by orbital resonances, in this case, with Jupiter.

Some asteroids are not in the asteroid belt but instead have orbits that reach in to and even inside the orbit of the Earth. A few have orbits that are entirely inside the orbit of the Earth. Such objects can be dangerous — they could hit the Earth.

More than half a dozen asteroids have been visited by spacecraft and imaged in detail. Being small, all are irregular bodies with many, many impact craters. Clearly there have been many collisions in their past histories, and (of course) the scars last essentially forever. At least one asteroid (Ida) has a moon (Dactyl), and others appear to be very loosely bound fragments.

Deimos and Phobos, the moons of Mars, are exactly like asteroids — small, irregular rocks covered in craters and debris. The may be captured asteroids.

The surface gravity of an asteroid or a moon that is only a few tens of km in diameter is tiny. A typical person would weigh only a few ounces. An astronaut could easily throw something into orbit around such a tiny world, or even throw it completely off to infinity.

Our Moon and Mercury
Summary

Our Moon and Mercury are very similar. Both are much smaller than the Earth; their surface gravities are low enough so that they have not been able to hold onto significant atmospheres. As a result, there is no erosion except by meteorite impact. Therefore the Moon and Mercury both have very old surfaces that are heavily cratered. Neither shows signs of tectonic activity — there is no continental drift. The surface rocks are frozen solid and essentially dead.

The Moon is mostly made of rock, but Mercury is a metal ball with a thin rocky crust.

The lunar highlands and all of Mercury are covered with craters. Most are more than 4 billion years old. They are the scars of the time when planets formed — when they (and the Earth, too) were frequently bombarded by major planetesimals and countless chunks of debris.

The largest impacts made enormous craters ringed by mountain chains. Some craters filled with lava. Those that did not are impact basins such as Orientale on the Moon and Caloris on Mercury.

The crust on the Earth-facing side of the Moon is thin, so big impacts punctured it and allowed lava to flood the low-lying plains and impact basins. This produced the dark lunar maria or “seas”. They are 3 to 4 billion years old. There are no maria on the far side of the Moon or on Mercury.

On the Moon, micrometeorite erosion wears away about 1 cm over every 2 million years. Astronaut footprints will last for several million years.

Our Moon is the only world other than the Earth that has personally been visited by humans.