ASTR 1P01
Brock University
Prof. Barak Shoshany

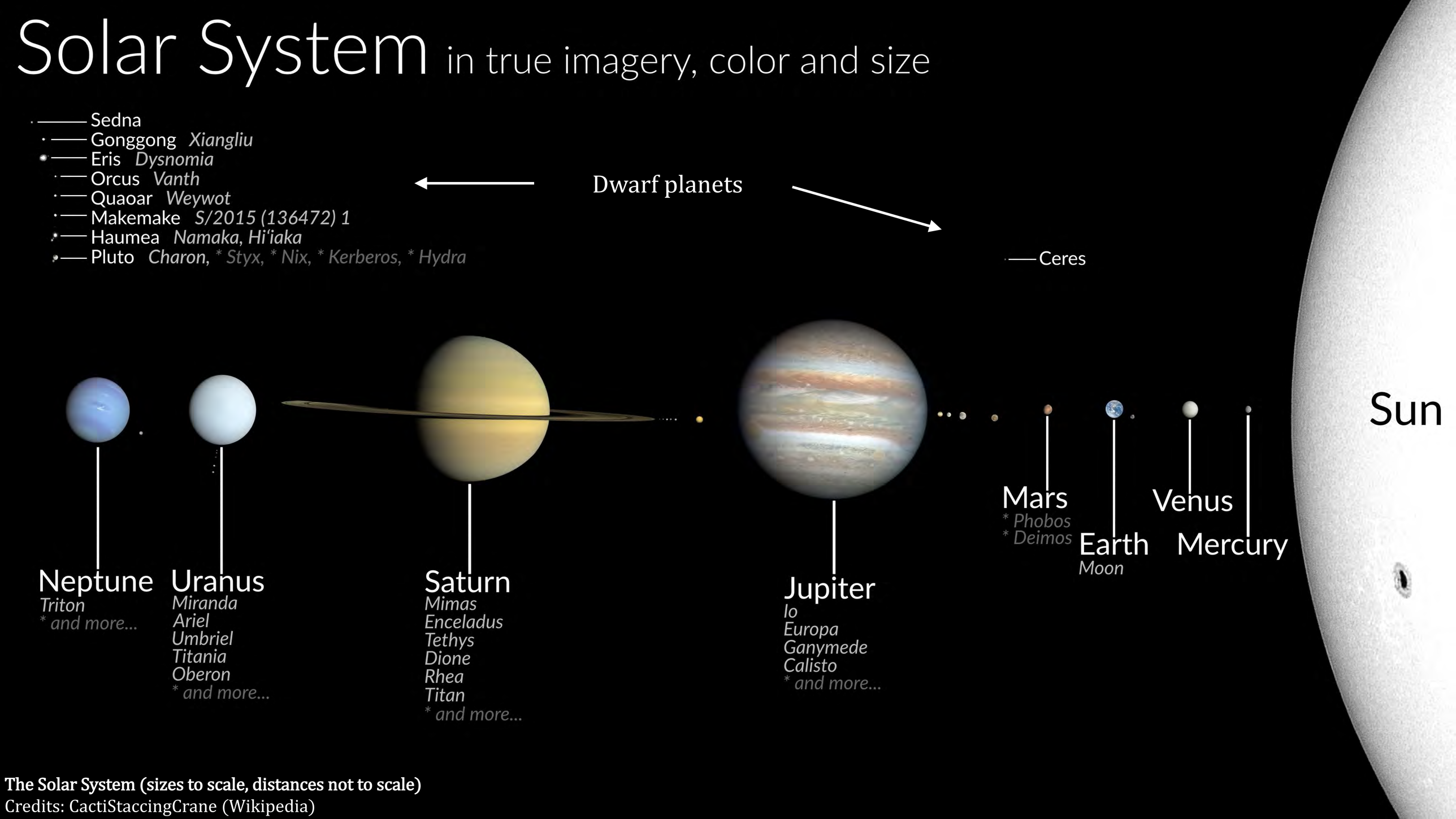
Lecture 10: Objects in the solar system

We will learn about…

- The composition and structure of planets, moons, comets, asteroids, and more.

Saturn’s rings, as seen by Cassini from a distance of 725,000 km
Credits: NASA/JPL-Caltech/Space Science Institute

Solar System in true imagery, color and size



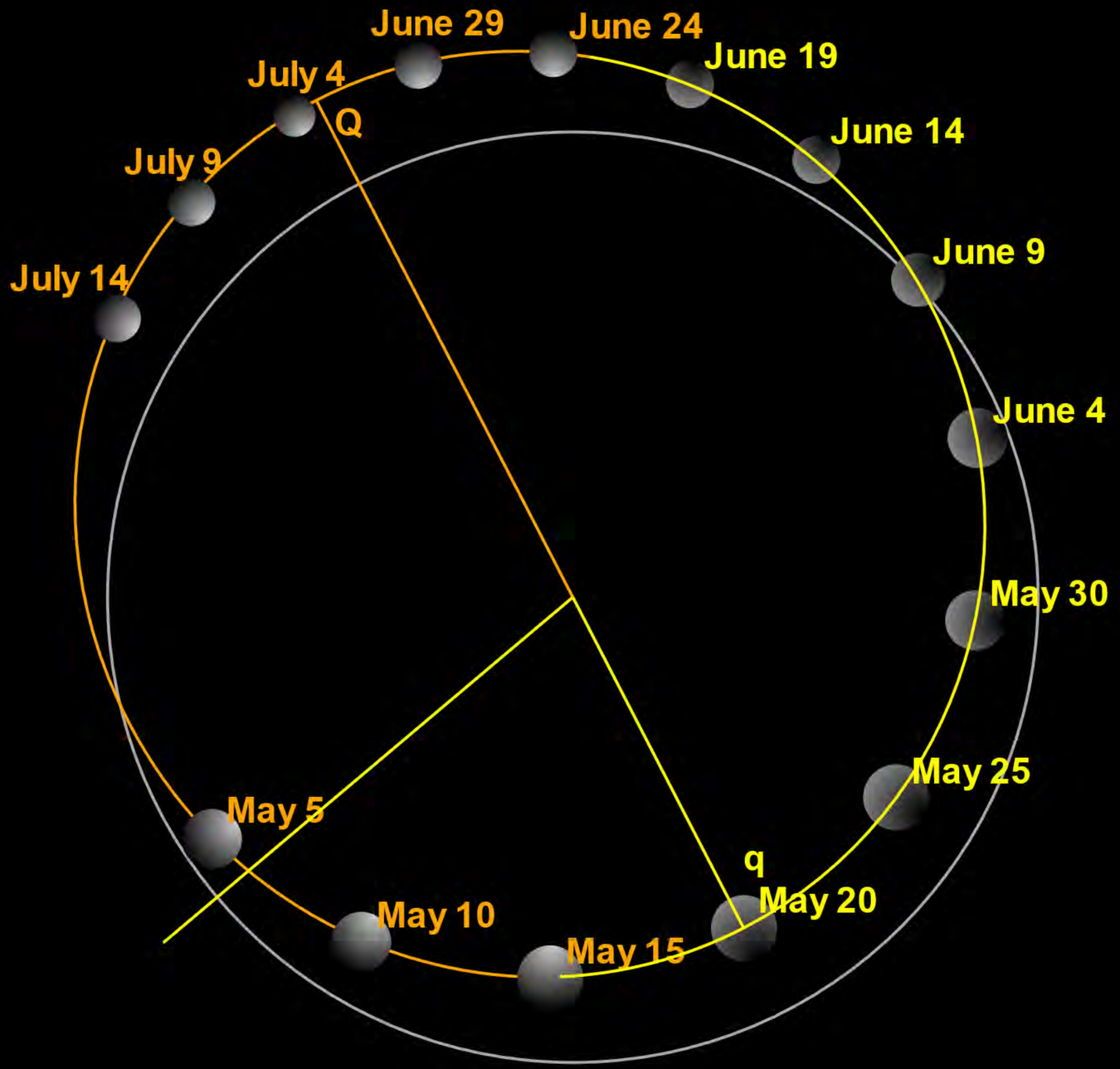
The Solar System (sizes to scale, distances not to scale)
Credits: CactiStaccingCrane (Wikipedia)

Mercury

- Mercury is the nearest planet to the Sun.
- From its surface, the Sun appears 3 times as large as it does from Earth, and sunlight is 7 times brighter.
- Its semi-major axis (average distance from the Sun) is ~58 million km or 0.39 AU.

Mercury

- Mercury's orbital eccentricity is 0.206, which is the largest among the 8 planets. This means its distance from the Sun varies greatly.
- At aphelion (farthest point from the Sun), the distance is ~70 million km.
- At perihelion (closest point to the Sun), the distance is ~46 million. That's ~2/3 of the aphelion.



The eccentric orbit of Mercury (in yellow) compared to a circular orbit with the same semi-major axis (in grey)
Credits: Eurocommuter (Wikipedia)

Mercury

- Mercury is an interior planet, meaning that its orbit lies between the Sun and Earth's orbit.
- This means that, looking from Earth, Mercury always appears within 28° of the Sun in the sky.
- This means Mercury can be seen near the western horizon after sunset or the eastern horizon before sunrise.

Mercury

- Since Mercury is an interior planet, we can see it pass in front of the Sun. This is called a transit of Mercury.
- This happens only rarely, 13-14 times per century, and only in May or November, due to the relative alignments of the orbits.
- The last transit of Mercury was November 11, 2019, and the next will occur on November 13, 2032.
- A transit is somewhat similar to a solar eclipse: an object is blocking the light from the Sun. However, Mercury is much smaller in the sky than the Moon, so it blocks only a tiny part of the Sun.

Transit of Mercury on November 11, 2019
Credits: NASA/Joel Kowsky

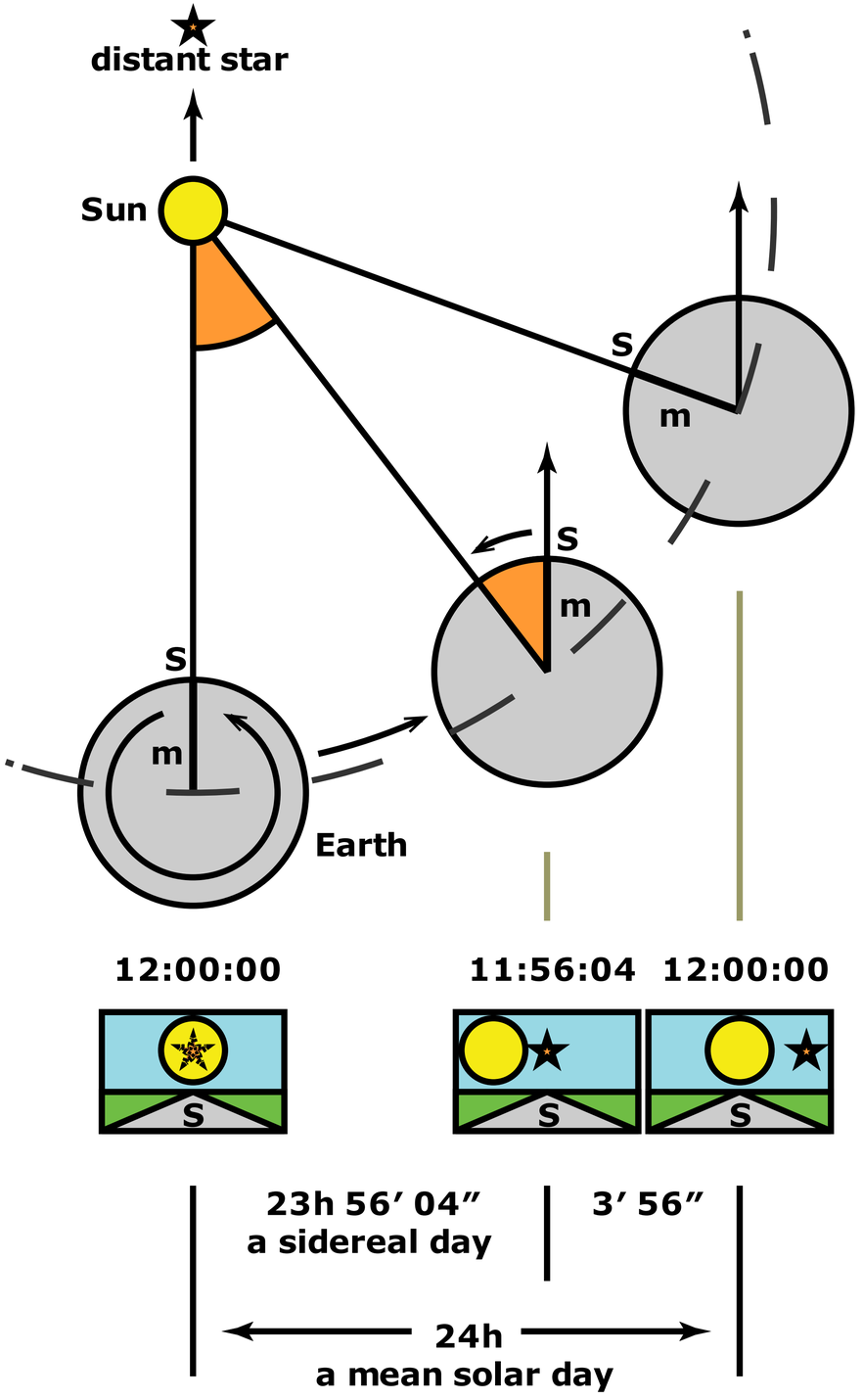
Mercury

- Mercury’s orbital period around the Sun is ~88 Earth days. It is the shortest among the planets.
- It is tidally locked with the Sun in a 3:2 spin-orbit resonance.
- This means it spins 3 times on its axis for each 2 orbits around the Sun.
- Mercury is the only tidally locked planet in the solar system.

Mercury

- On Earth, days are obviously much shorter than years.
- Recall the two definitions of a day on Earth:
  - Solar or synodic day: How long the Sun takes to return to the same position in the sky (24 hours on Earth).
  - Sidereal day: How long a fixed star takes to return to the same position in the sky (23:56 hours on Earth).
- These are the same on Earth for most practical purposes.

- At 12:00 solar time on day 1, both the Sun and a fixed star are at the zenith.
- At 11:56 on day 2, the fixed star is back at the zenith. One sidereal day has passed.
- 4 minutes later, at 12:00 on day 2, the Sun is back at the zenith. One solar day has passed.



Sidereal Time vs. Solar Time
Credits: Xaonon (Wikipedia)

Mercury

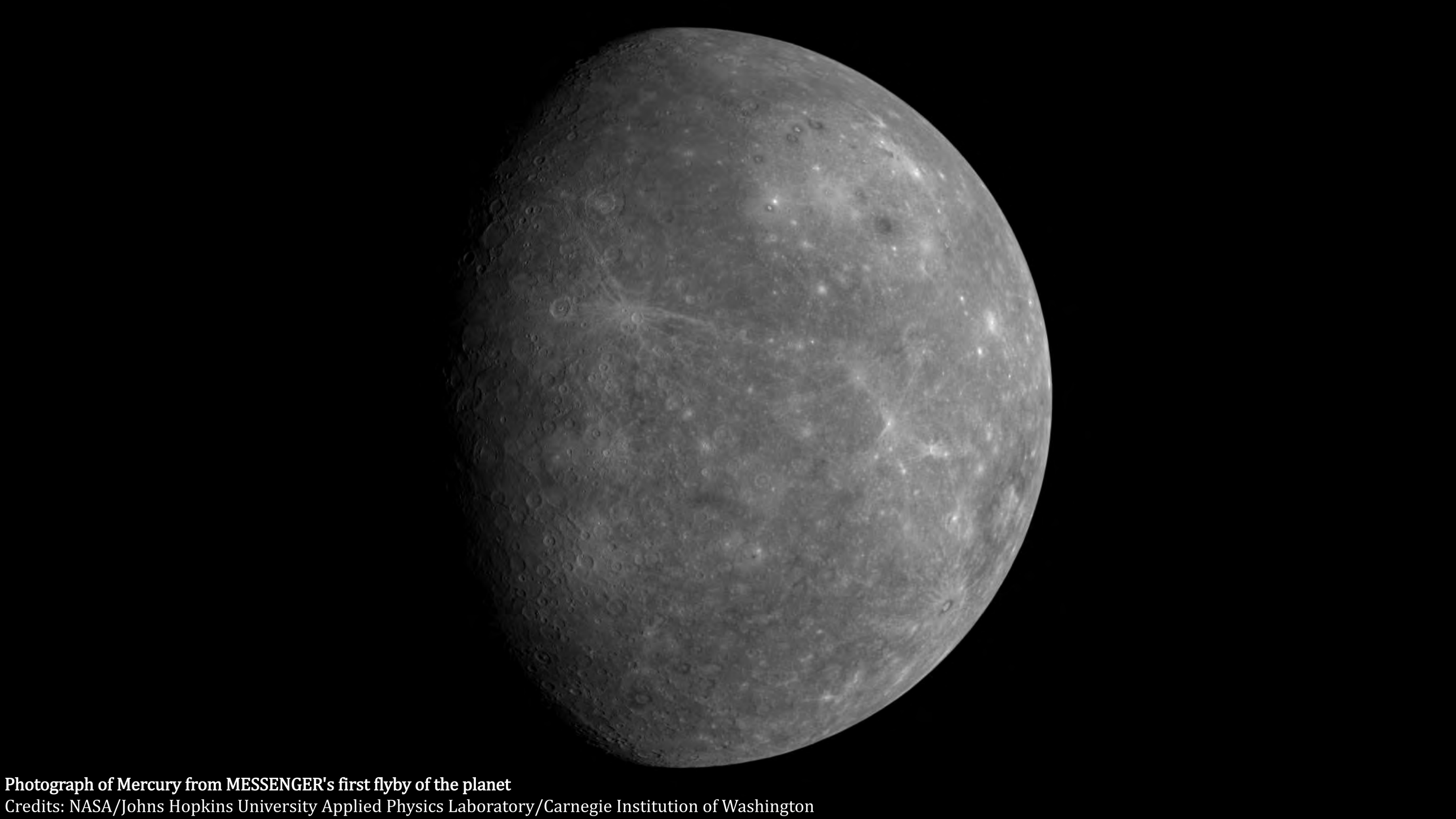
- But this is not the case on Mercury, due to its 3:2 spin-orbit resonance.
- Mercury's sidereal day is ~58.65 Earth days, but its solar day is much longer: exactly 2 Mercury years, or ~176 Earth days.
  - Note that $58.65 \times 3 \approx 176$.
  - So 3 Mercury sidereal days = 2 Mercury years.

Mercury

- Mercury has the smallest axial tilt among the planets, ~0.03° (basically zero). Compare this with Earth's axial tilt of ~23.4°.
- This means Mercury does not experience any seasons.
- It also has no atmosphere to retain heat. Therefore, its surface temperatures vary more than any other planet during the day.
- The temperatures range from ~100 K (−173 °C) at night to ~700 K (427 °C) during the day at the equator.
- The polar regions are constantly below ~180 K (−93 °C).

Mercury

- Mercury has no moons.
  - Mercury and Venus are the only 2 planets in the solar system that do not have moons, probably because they’re too close to the Sun.
- The surface of Mercury is heavily cratered, similar to the Earth’s Moon.
- This indicates that it has been geologically inactive for billions of years.



Photograph of Mercury from MESSENGER's first flyby of the planet
Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

The Picasso crater on Mercury
Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

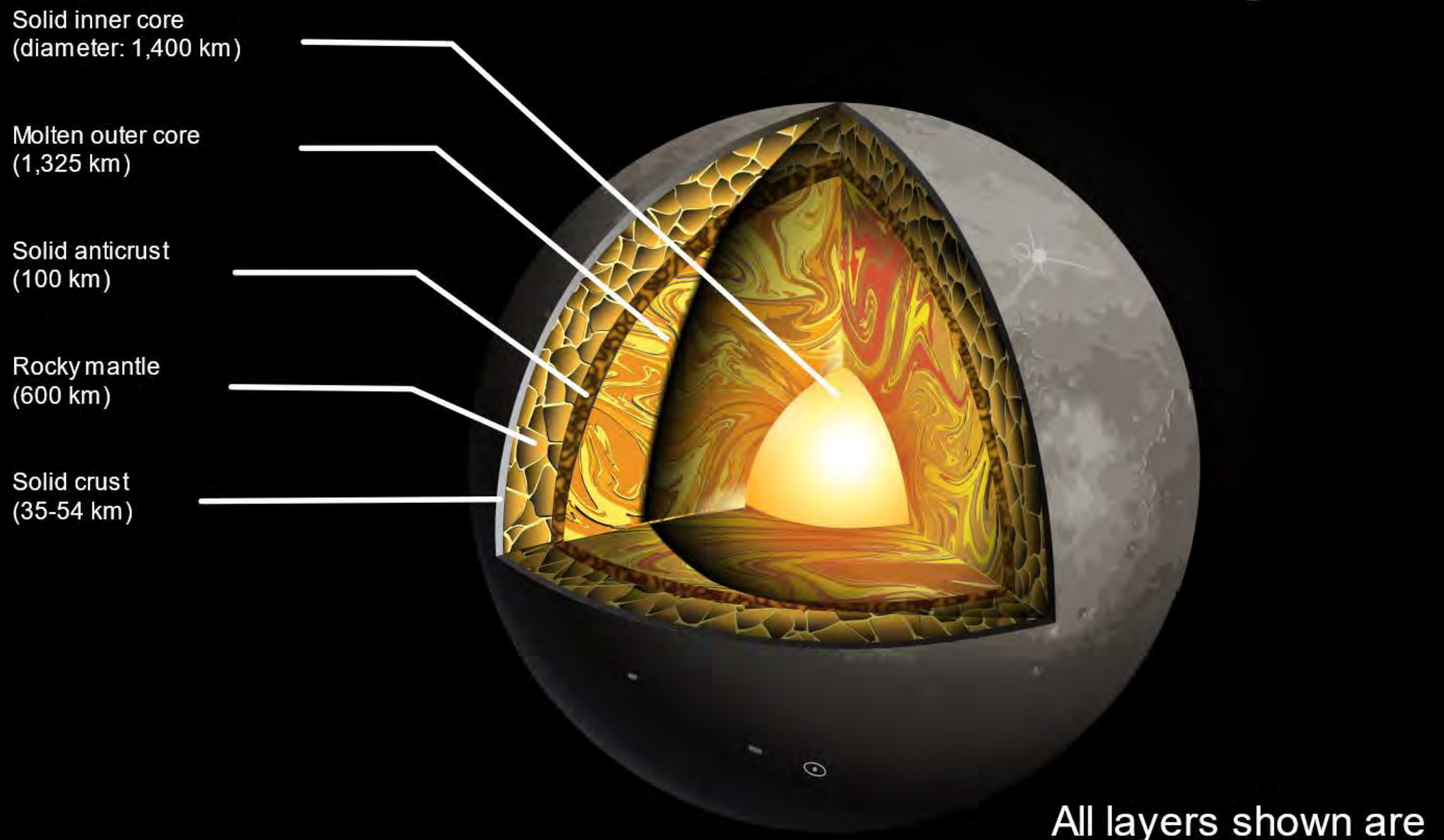
Mercury

- Mercury's mass is 3.3×10^{23} kg. This is 18 times smaller than Earth's mass, and the smallest mass among the planets.
- It also has the smallest radius: ~2,400 km, which is ~38% the radius of Earth.
- Its mean density is ~5,400 kg/m^3, the second highest among the planets.
  - The most dense planet is Earth, at a slightly higher ~5,500 kg/m^3.

Mercury

- Due to this high density, we know Mercury must be composed of heavier materials, such as metals.
- We think it has a metallic iron-nickel core taking up 60% of its mass.
- At least part of the core must be liquid, since Mercury has a (weak) magnetic field, and a liquid core would generate this field.
- The rest of the planet is made up primarily of silicates, rocks composed of silicon and oxygen atoms.
- Like most other planets, the internal structure consists of an inner core, a middle mantle, and an outer crust.

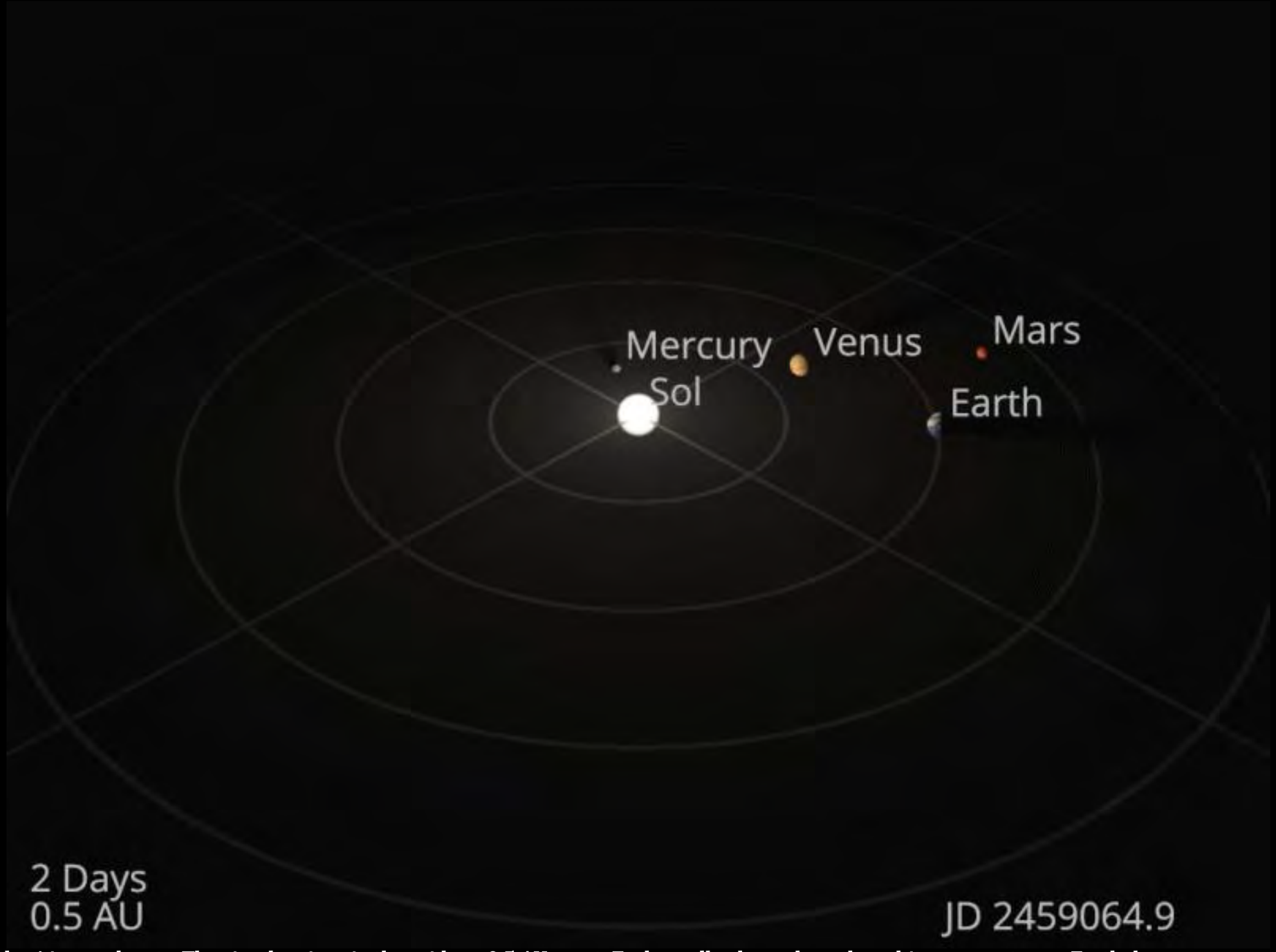
Mercury



Layers of Mercury, including the core, mantle, and crust
Credits: A loose necktie (Wikipedia)

Venus

- Venus is the second planet from the Sun.
- Its semi-major axis is 108 million km or 0.72 AU, roughly twice that of Mercury.
- Venus, like Mercury, is an interior planet, meaning that its orbit lies between the Sun and Earth’s orbit.
- Therefore, it always appears close to the Sun as seen in Earth’s sky.
- Venus is also the brightest planet in the sky. It can be visible to the naked eye during the day, and can even cast shadows at night.
- Like Mercury, Venus does not have any moons.



Animation of the orbits of the 4 inner planets. The circular rings in the grid are 0.5 AU apart. Each small sphere along the orbit represents one Earth day.
Credits: Datumizer (Wikipedia); animation URL: https://en.wikipedia.org/wiki/File:Solar_system_orrery_inner_planets.gif

Simulation

- I will show how to find Mercury and Venus in the sky using Stellarium.
- They are both always within 28° of the Sun and therefore easiest to see at sunrise or sunset.
- However, Venus is much easier to find, as it is always the brightest planet in the sky. Mercury is usually hard to see.
- Stellarium is freely available at this URL:

https://stellarium.org/

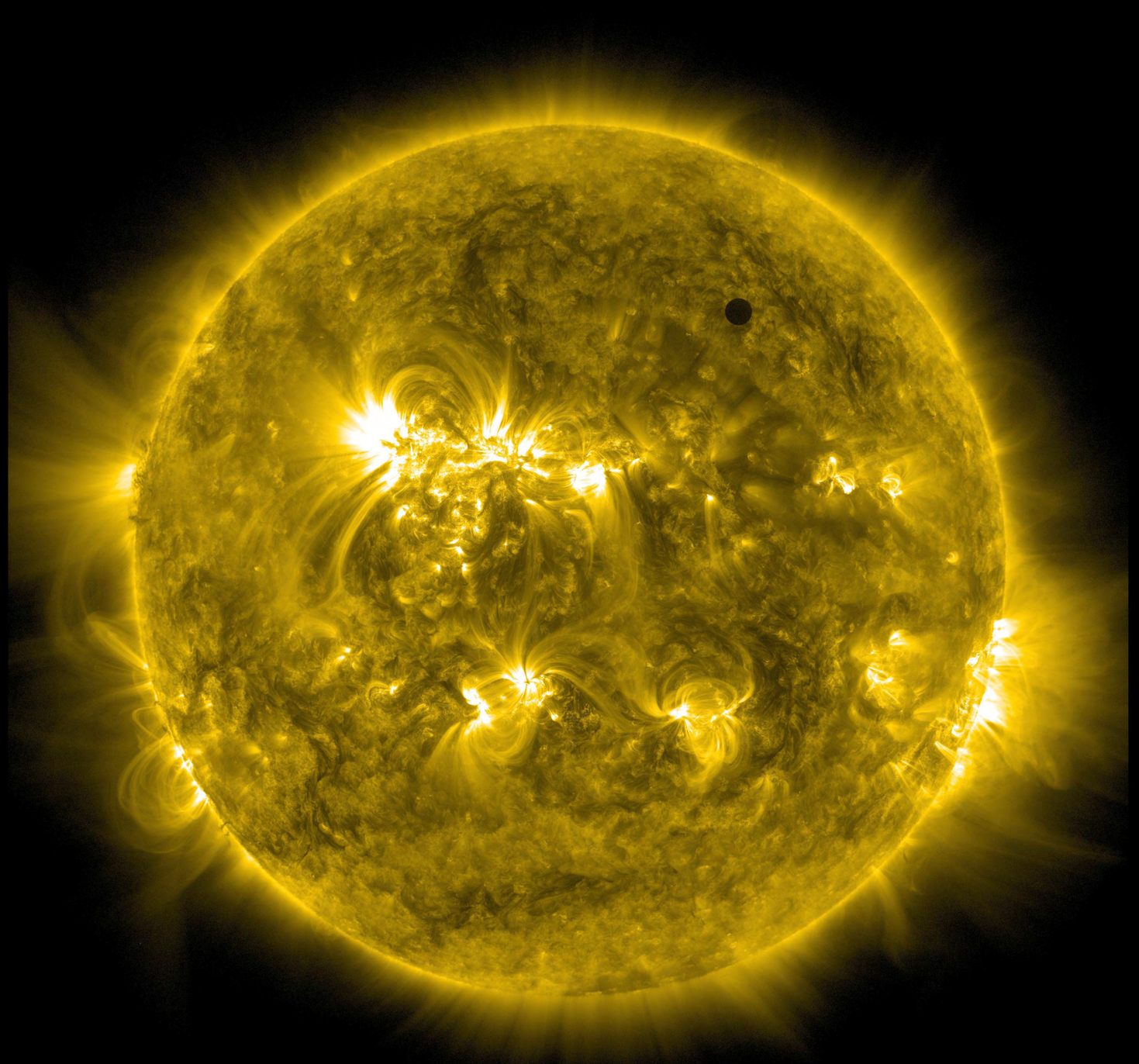
Simulation

- Venus can get closer to Earth than any other planet: ~40 million km at its closest approach.
- This also means it's easiest to get from Earth to Venus than any other planet (if you time it correctly). Therefore, Venus was the first planet humans sent spacecrafts to (Venera 1 in 1961)
- But Mercury is actually closer to Earth than Venus most of the time!
- I will demonstrate why using an online simulation.
- The simulation can be found at this URL

https://engaging-data.com/mercury-closest/

Venus

- Since Venus is an interior planet, it can also pass directly in front of the Sun as seen from Earth. This is called a transit of Venus.
- These transits are extremely rare. They occur in pairs 8 years apart. Each pair is separated from the next pair by 105 or 121 years.
- The last pair of transits of Venus was June 8, 2004 and June 5, 2012.
- The next pair will be December 10, 2117 and December 8, 2125.
- Historically, Venus transits had great importance as they were used to accurately estimate the size of the solar system, as early as 1639.



Transit of Venus on June 5, 2012, as seen by NASA's Solar Dynamics Observatory in the extreme ultraviolet range
Credits: JAXA/ISAS/DARTS/Kevin M. Gill

Video

- I will show a video from NASA's Solar Dynamics Observatory showing the 2012 transit of Venus in different wavelengths. (The image in the previous slide was taken from that video.)
- The video can be found at this URL

  https://svs.gsfc.nasa.gov/vis/a010000/a010900/a010996/index.html

Venus

- Venus is covered by dense clouds of sulfuric acid (H_2SO_4), which reflect ~70% of the sunlight that falls on them.
- This makes it very hard to see its surface, even from cameras in orbit around it.

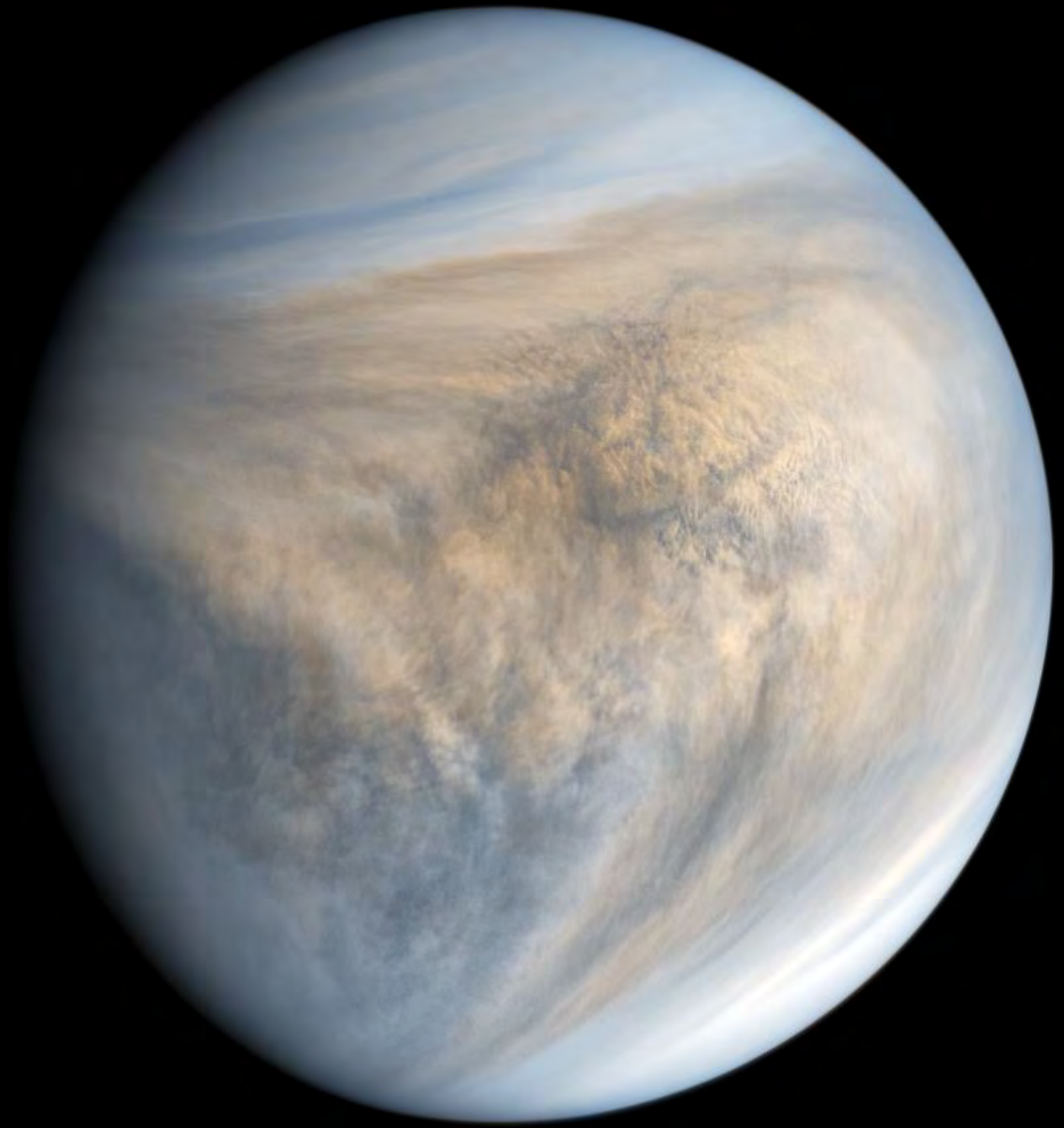
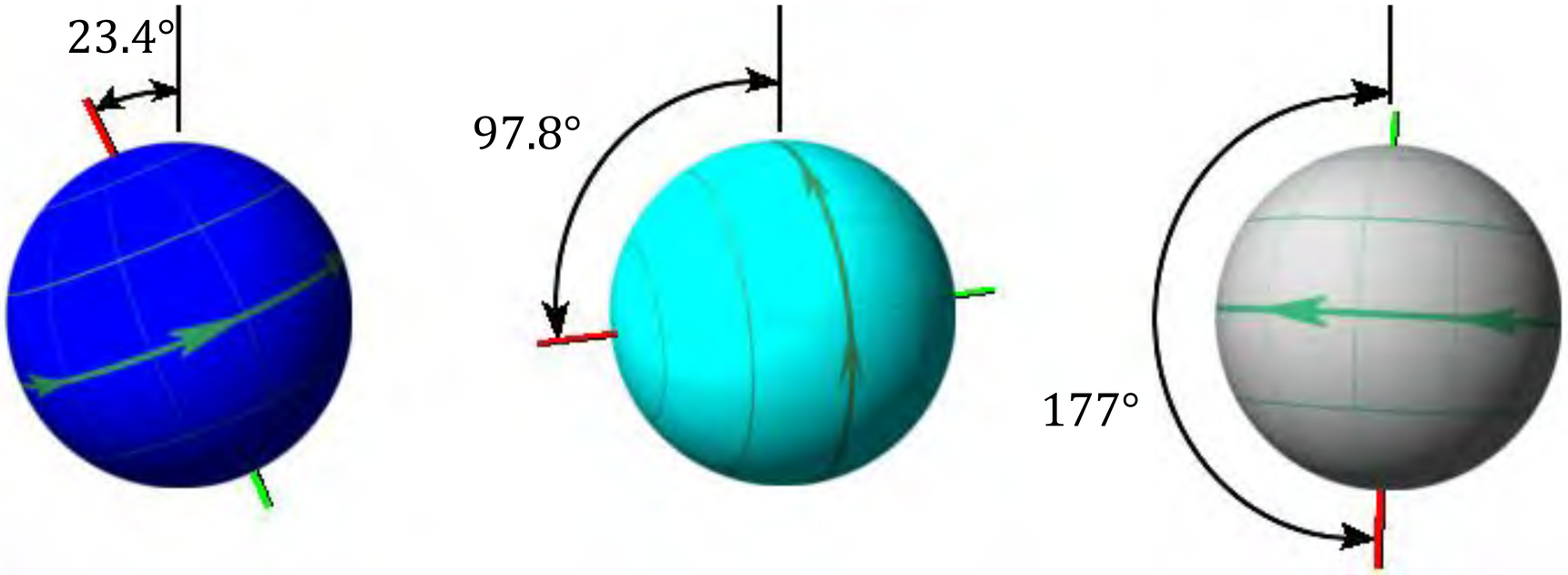


Image of Venus’s cloud structure in the ultraviolet band, as taken by Akatsuki, Japan’s Venus Climate Orbiter
Credits: JAXA/ISAS/DARTS/Kevin M. Gill

Venus

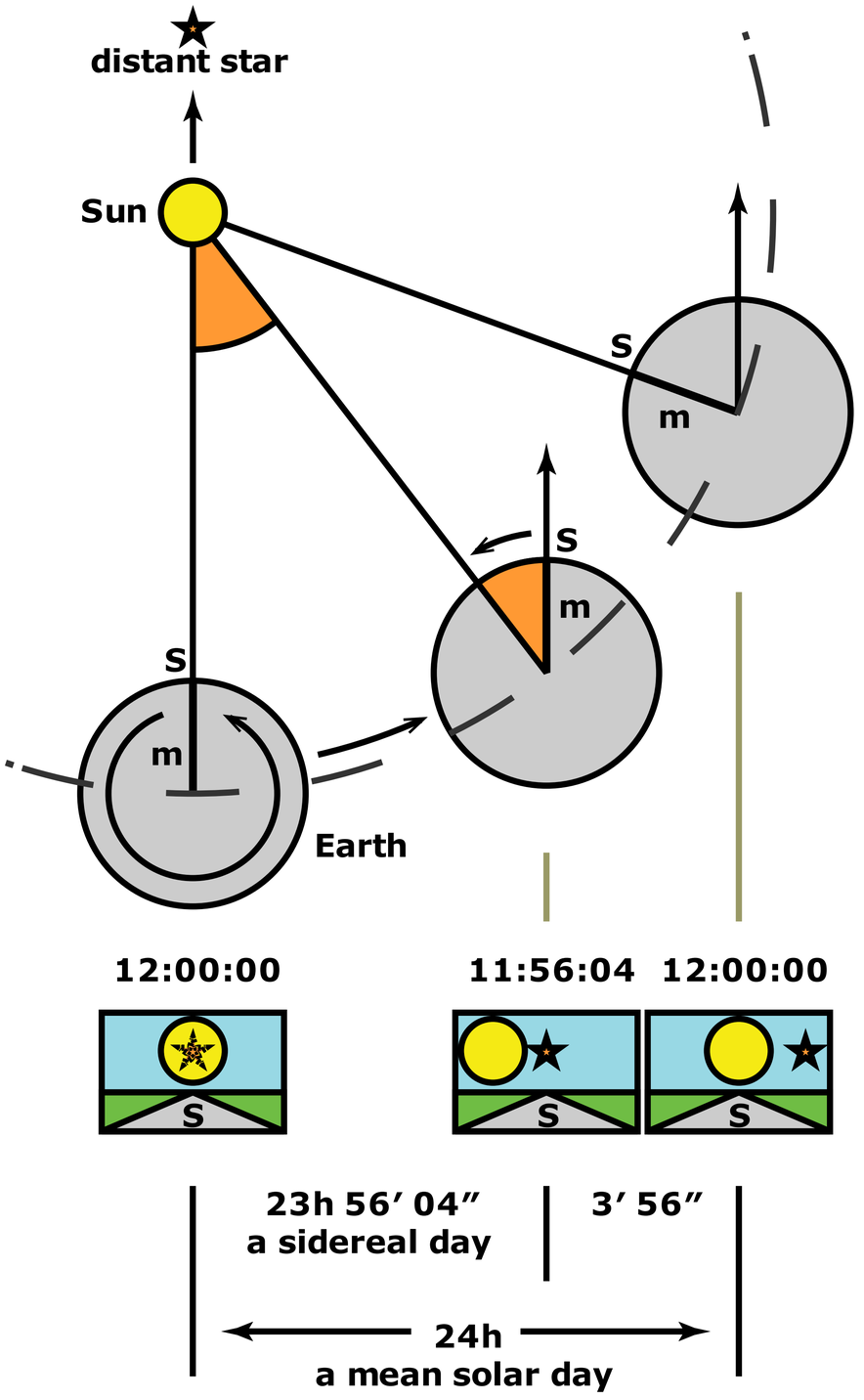
- All planets in the solar system revolve around the Sun counterclockwise, as viewed from above the Sun's north pole.
- Most planets also spin around their axes in the same direction.
- However, there are two exceptions. Venus and Uranus have retrograde rotation: they spin around their axes clockwise, opposite to their direction of revolution around the Sun.
- This means that on Venus and Uranus, the Sun rises in the west and sets in the east!

- Venus's axial tilt is ~177°, very close to 180°, indicating that the rotational axis is tilted “upside-down” compared to the orbital axis.
- Uranus’s axial tilt is ~97.8°, close to 90°, indicating that the rotational axis is tilted almost perpendicular to the orbital axis.
- Compare this with the Earth’s axis tilt of 23.4°.



Credits: Modification of work by Tfr000 (Wikipedia)

- 1 solar year on Venus is ~225 Earth days.
- 1 solar day on Venus is ~117 Earth days.
- 1 sidereal day on Venus (full rotation with respect to fixed stars) is ~243 Earth days.
- It is the longest sidereal day among all the planets.
- The sidereal day is longer than the solar day, unlike Earth or Mercury, because Venus has retrograde rotation.
- In other words, the effect is the opposite of what's illustrated here for Earth.



Sidereal Time vs. Solar Time
Credits: Xaonon (Wikipedia)

Simulation

- I will illustrate Venus's retrograde rotation around its axis using Universe Sandbox:

https://universesandbox.com/

- I will also show how Mercury and Venus rotate much slower compared to Earth and Mars (which is why the days on Mercury and Venus are much longer).

Venus

- Venus has a radius of ~6,050 km. This is very similar to the radius of Earth (~6,370 km).
- Its mean density is ~5,200 kg/m^3, slightly lower than Earth's (~5,500 kg/m^3).
- Its mass is ~4.9×10^{24} kg, ~82% of Earth's mass (~6.0×10^{24} kg).
- Venus is sometimes called Earth's "sister" or "twin" planet due to their similarity in size and mass.

Venus

- However, Venus has a very different climate and atmosphere.
- The atmosphere of Venus consists mainly of carbon dioxide (CO_2), and it is the densest and hottest among the 4 terrestrial planets.
- The atmospheric pressure at the surface of Venus is ~92 times that of Earth.
- The average surface temperature of Venus is 737 K (464 °C).
- This is hotter than even the maximum daytime temperature on Mercury, ~700 K (427 °C), and obviously much hotter than Earth.

Venus

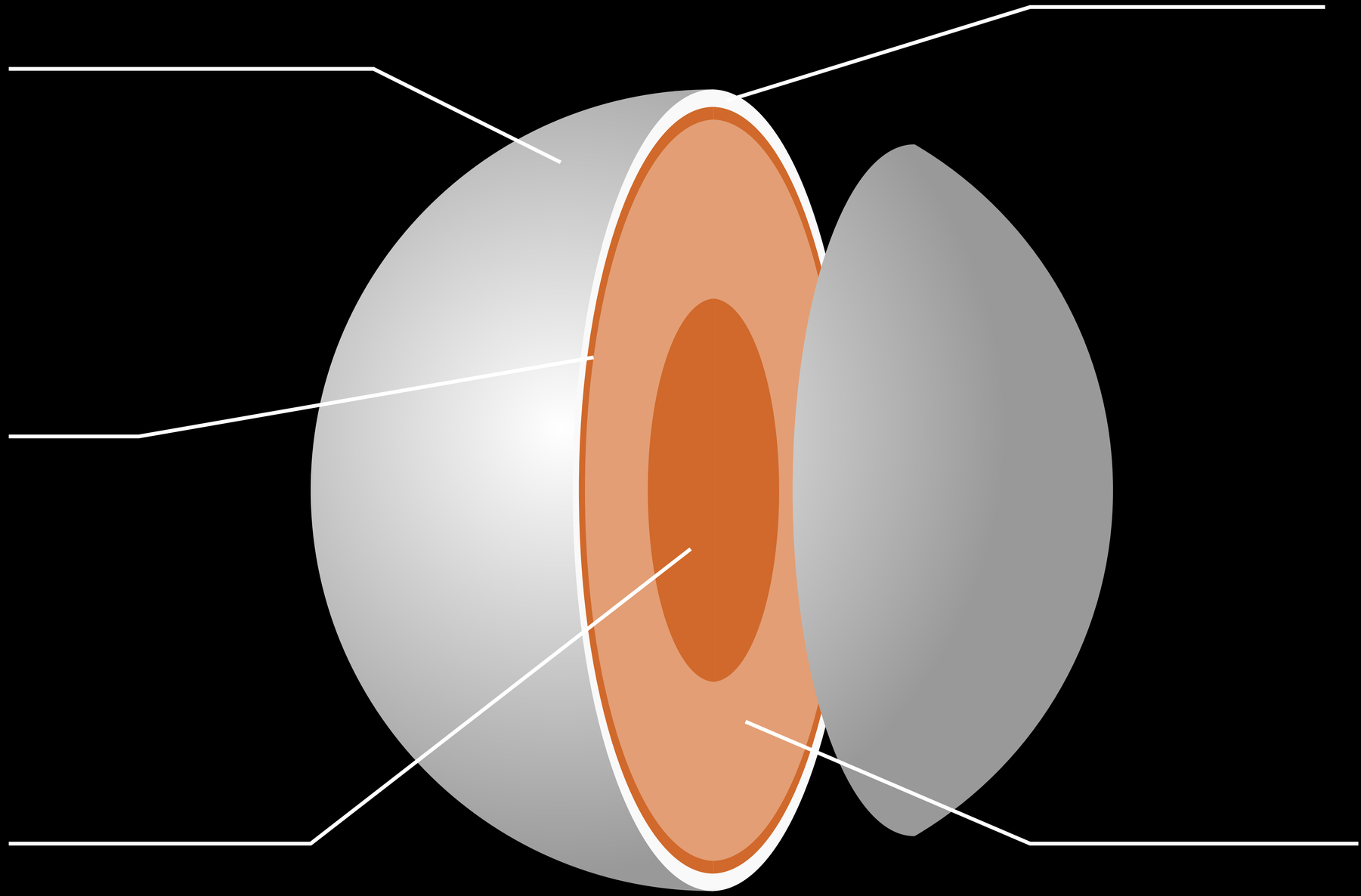
- Venus is a bit closer to the Sun than Earth, so it gets some more intense sunlight.
- However, this is not nearly enough to explain why its surface is so much hotter than Earth.
- Also, Mercury is even closer to the Sun than Venus, but it is colder!
- The reason Venus is so hot is the greenhouse effect.

Venus

- The greenhouse effect also exists on Earth.
- After the Sun warms the surface of the Earth, the surface releases heat back in the form of infrared radiation.
- However, greenhouse gases, such as carbon dioxide (CO_2) and water vapor (H_2O), prevent heat from escaping back into space.
- This causes the overall temperature of the planet to increase.
- The same thing happens on Venus. However, Venus has a million times more CO_2 than Earth!
- This makes the greenhouse effect much stronger, and therefore the temperature gets much hotter.

Venus

- Venus may have had a climate similar to Earth, with moderate temperatures, water oceans, and CO_2 stored in the ocean and rocks.
- However, even a small amount of extra heat from the Sun can lead to increased water evaporation and release of gas from rocks.
- This increases the greenhouse gases CO_2 and H_2O in the atmosphere.
- So this process amplifies itself: more heat → more greenhouse gases → more heat → more greenhouse gases → and so on.
- Eventually the oceans boil completely.
- This is called the runaway greenhouse effect.



We don’t know much about the internal structure of Venus, but it should have a differentiated structure with a core, mantle, and crust, like Earth and Mercury.
Credits: Urutseg (Wikipedia)

Mars

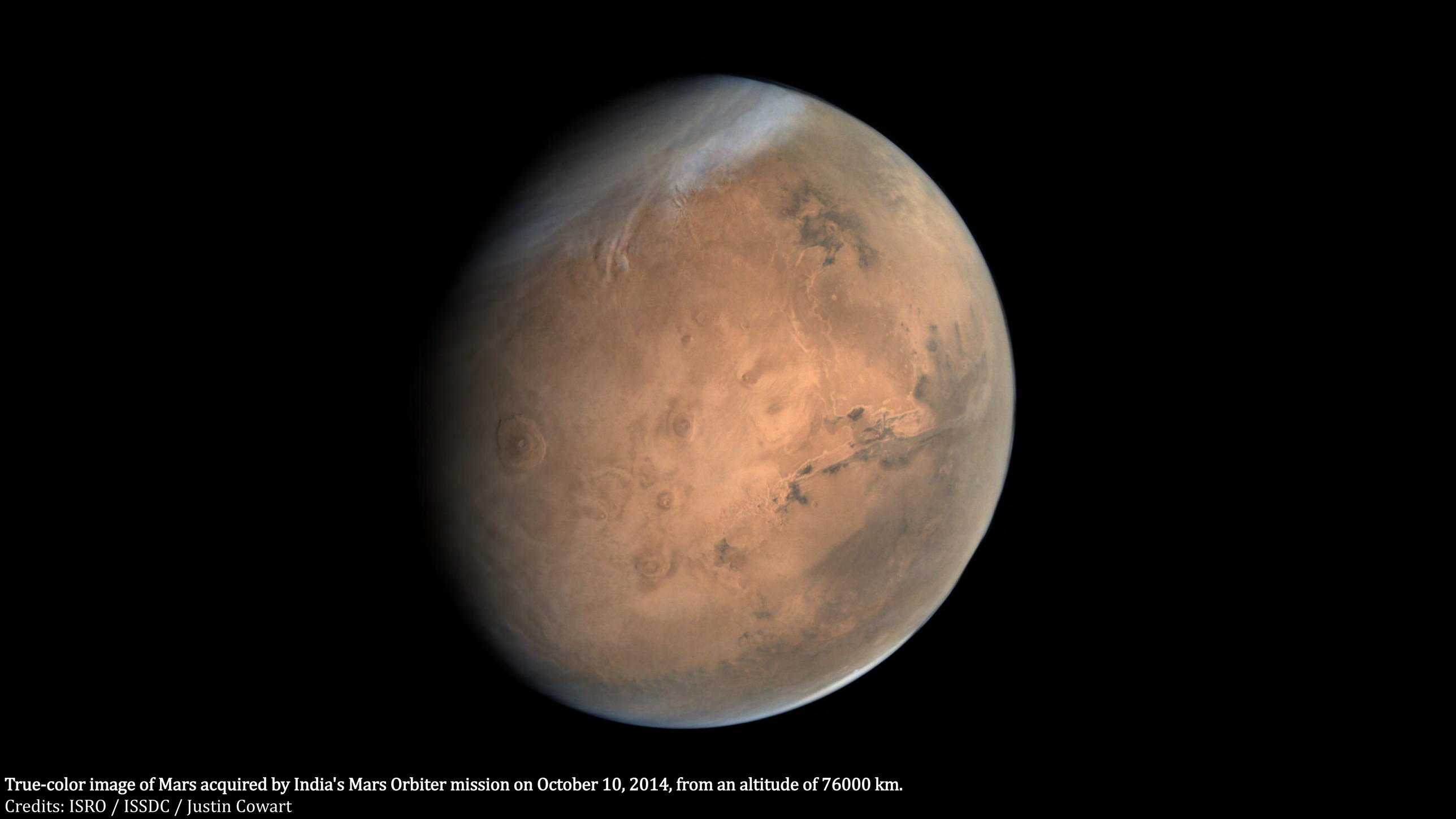
- Mars is the fourth planet from the Sun, and the farthest planet in the inner solar system, after Mercury, Venus, and Earth.
- Its semi-major axis is ~228 million km or ~1.5 AU.
- It is the second-smallest planet, with a radius of ~3,900 km (larger only than Mercury, which has a ~2,400 km radius).
- It has a very thin atmosphere, less than 1% the density of Earth's atmosphere.

The terrestrial planets. Sizes to scale, distances not to scale.
Credits: NASA/JHUAPL; NASA/Johns Hopkins University APL/Carnegie Institution of Washington; NASA/Apollo 17 crew; ESA/MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA

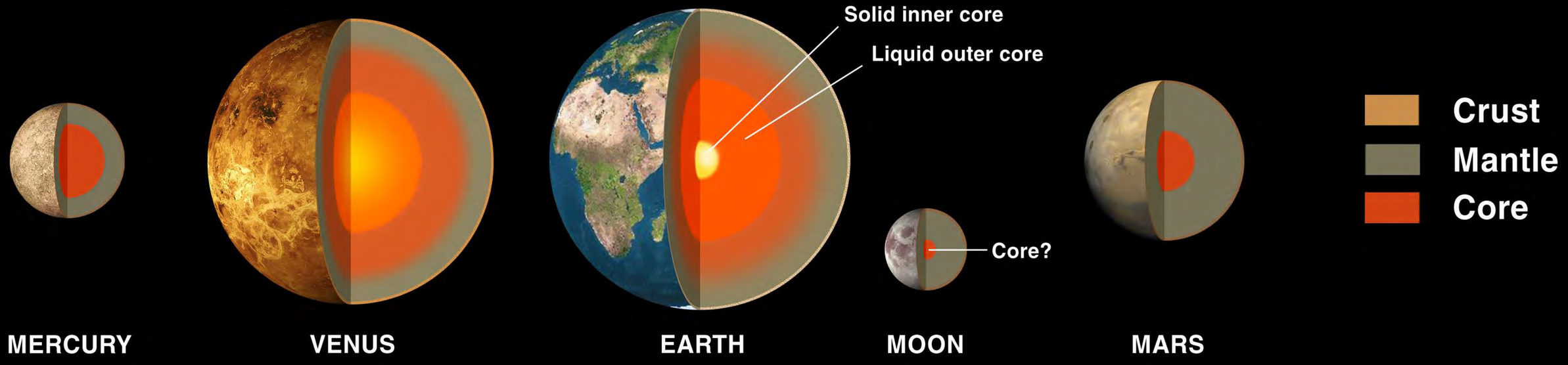
Mars

- Like Mercury, Venus, and Earth, Mars is a terrestrial planet, composed primarily of silicates and metals.
- It has a core of iron and nickel, like Earth.
- Mars is sometimes called the Red Planet due to its reddish color, caused by iron oxide in its surface.

A sample of Iron(III) oxide, illustrating its red color.
Credits: Benjah-bmm27 (Wikipedia)



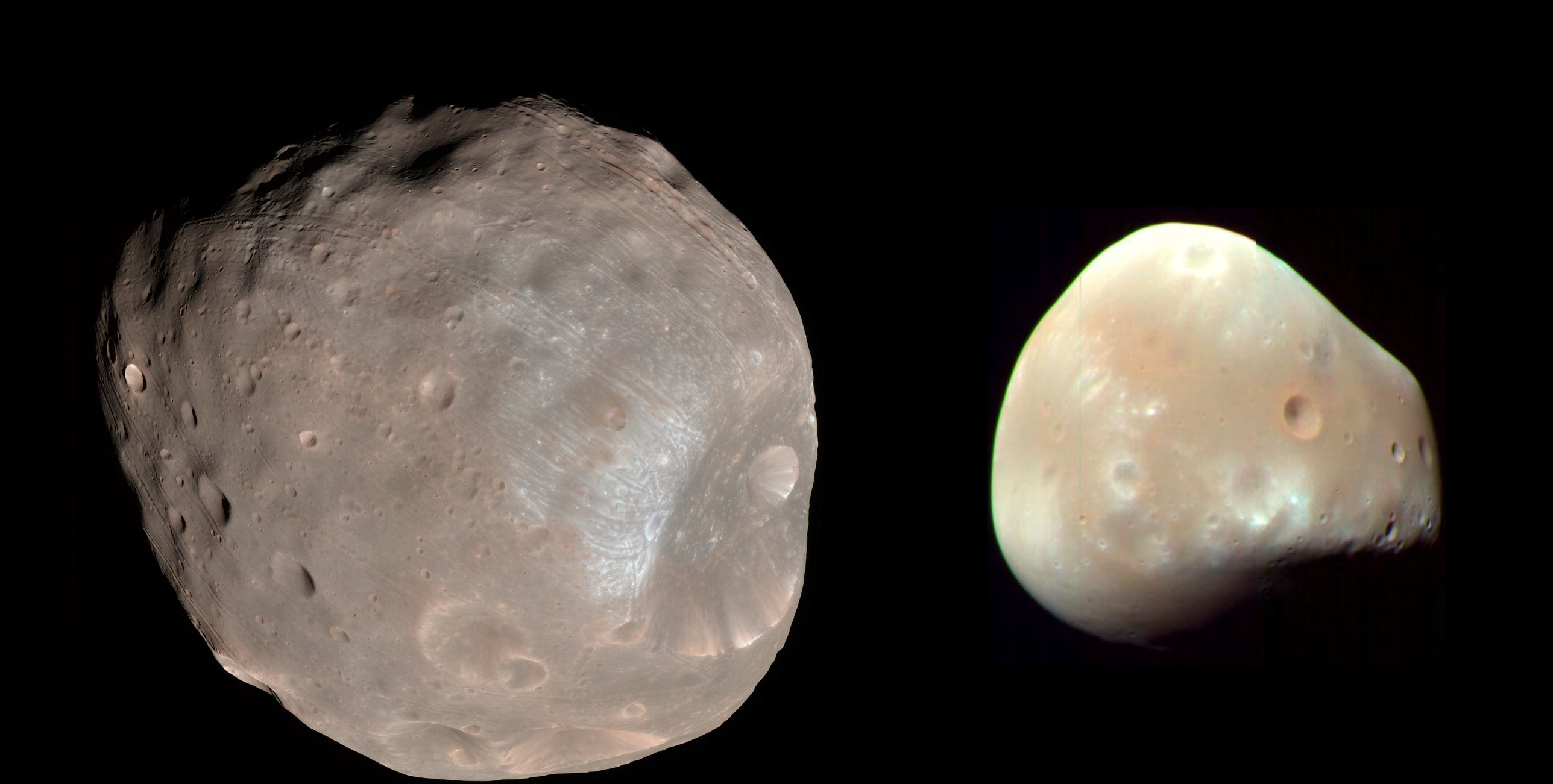
True-color image of Mars acquired by India's Mars Orbiter mission on October 10, 2014, from an altitude of 76000 km.
Credits: ISRO / ISSDC / Justin Cowart



Comparison of the internal structure of the inner planets (and Earth's moon).
Credits: NASA

Mars

- A Martian solar day is 24 hours and ~39 minutes, remarkably close to a solar day on Earth.
- A Martian year is ~687 Earth days long (~1.9 Earth years).
- The axial tilt of Mars is ~25.2°, very close to that of Earth (~23.4°).
- This means Mars has seasons, like Earth does, but they are almost twice as long, since the Martian year is longer.
- Mars has two moons: Phobos and Deimos.



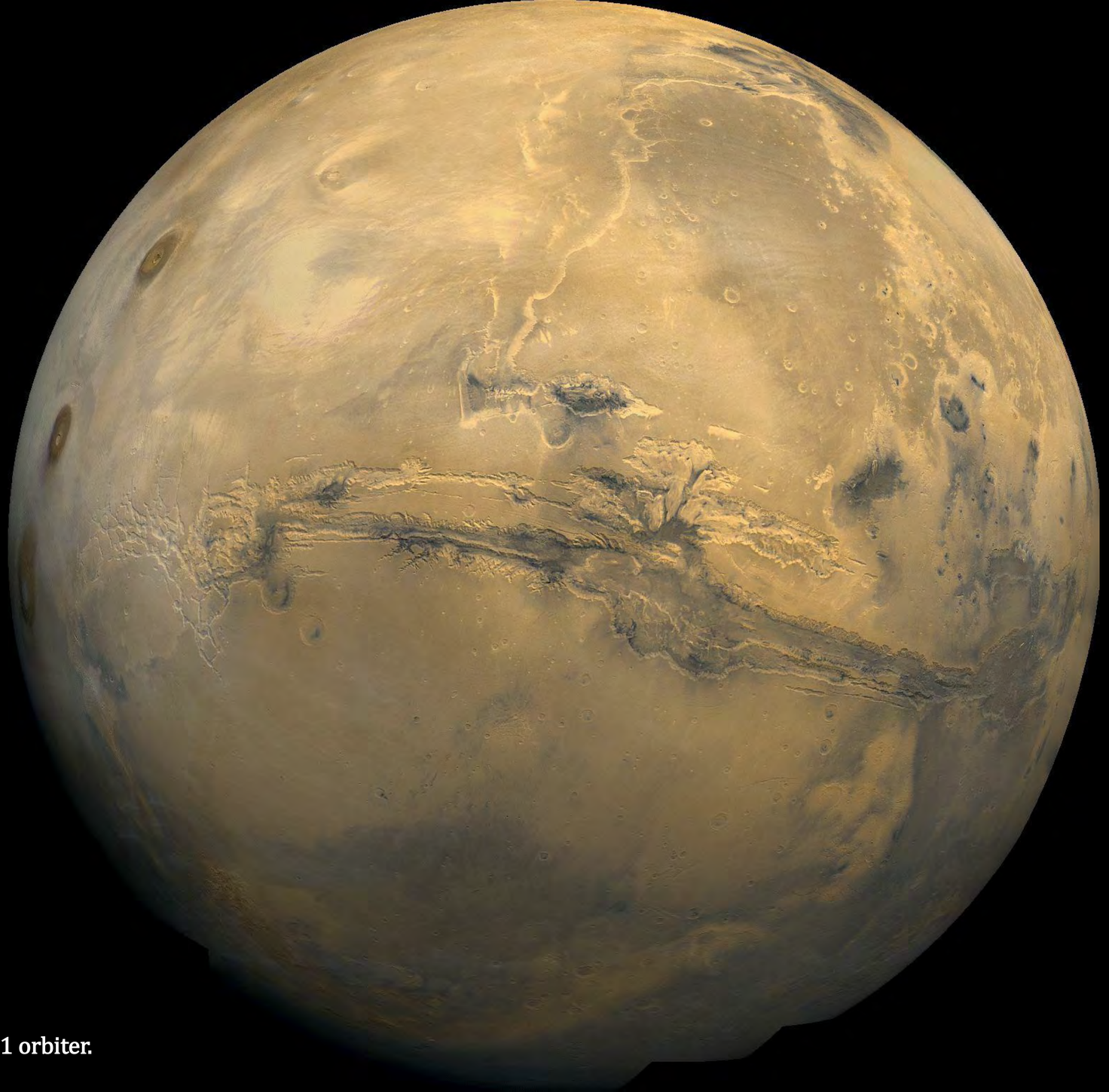
The moons of Mars: Phobos (left) and Deimos (right).
Credits: NASA / JPL-Caltech / University of Arizona

Left: The moons of Mars (Phobos is the larger one) in the Mars sky as seen by NASA's Curiosity rover from the surface of Mars. Right: view of Earth's moon in Earth's sky, for comparison.
Credits: NASA / JPL-Caltech / University of Arizona

Mars

- The surface of Mars has many volcanoes. However, it is unknown if it is still volcanically active today.
- Olympus Mons, a volcano on Mars, is the largest volcano and highest known mountain in the solar system.
  - It is ~22 km high. Compare this with Mount Everest, Earth's highest mountain, which is only ~8.8 km high!
- Valles Marineris, a system of canyons on Mars, is one of the largest canyons in the solar system.
  - It is ~4,000 km long, ~200 km wide, and ~7 km deep.

Olympus Mons as seen from the Viking 1 orbiter.
Credits: NASA



Valles Marineris as seen from the Viking 1 orbiter.
Credits: NASA / USGS

Mars

- Liquid water cannot exist on the surface of Mars due to its low atmospheric pressure.
- However, there is ice water on the surface, including both polar ice caps.
- There is likely more ice deep underground.
- In the past, Mars may have had liquid water on its surface.

The Korolev impact crater on Mars is estimated to contain ~2,200 km^3 of water ice.
Credits: ESA/DLR/FU Berlin

Mars

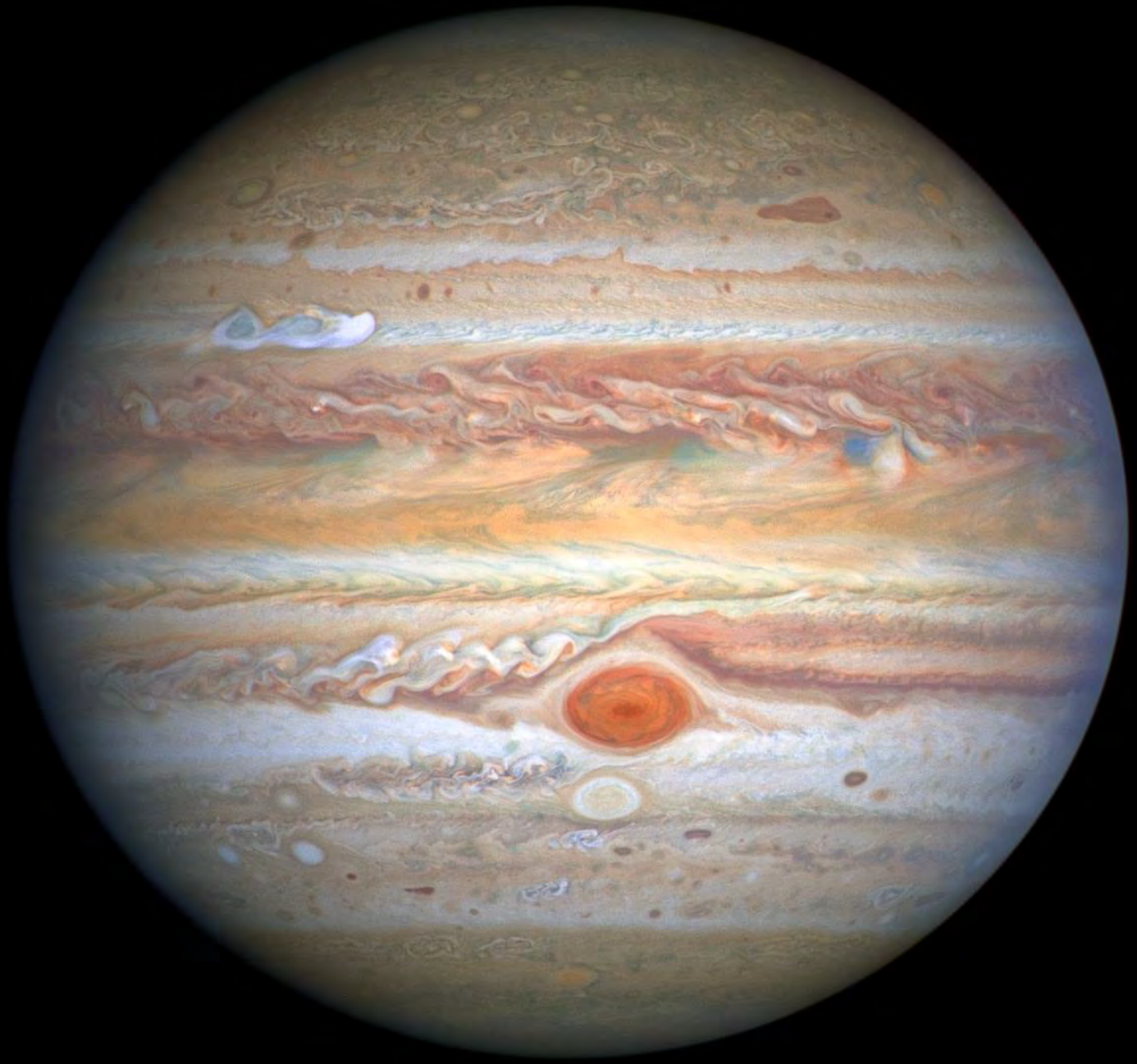
- If Mars had liquid water, then it could have been suitable for life (as we know it).
- However, we don’t know if Mars ever had any form of life.
- Mars is one of the most likely candidates for life in the solar system, due to its similarities with Earth.
- Looking for evidence of life on Mars is a primary objective of past and future Mars missions.
- Even if we find life, it will most likely be microorganisms, but that would still be extremely exciting!

Jupiter

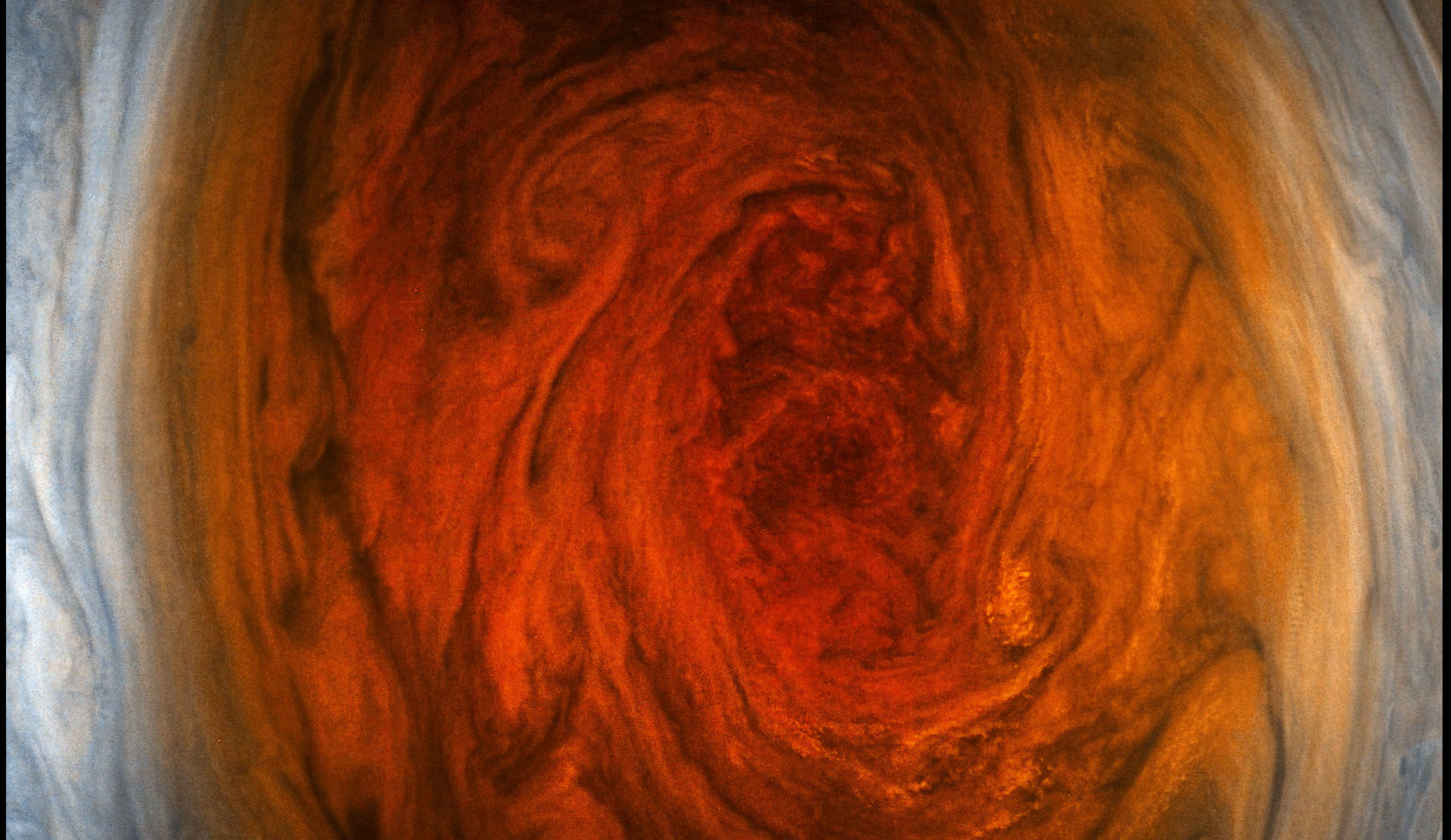
- Jupiter is the fifth planet from the Sun.
- Its semi-major axis is ~778 million km or ~5.2 AU.
- It is the largest planet in the solar system, with a mean radius of ~70,000 km, which is ~11 times Earth's radius.
- Jupiter is also the most massive planet, at $\sim 1.9 \times 10^{27}$ kg, which is ~318 times Earth's mass and ~1/1050 the Sun's mass.
- Its mass is more than 2.5 times that of all other planets combined!
- Jupiter is the third brightest celestial object in the Earth's night sky, after the Moon and Venus.

Jupiter

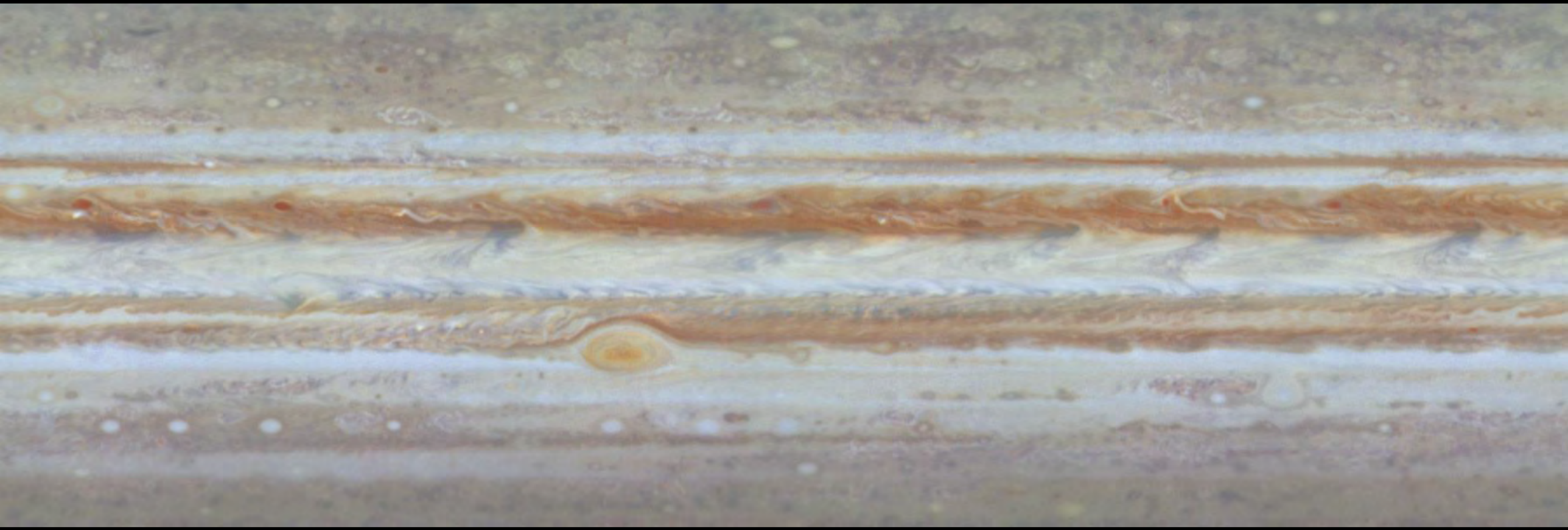
- Jupiter is primarily composed of hydrogen.
- It also contains helium: ~25% of its mass and ~10% of its volume.
- As a gas giant, Jupiter does not have a solid surface.
- However, it may have a rocky core of heavier elements at its center.
- Jupiter's atmosphere is made of bands, with storms along their boundaries.
- The most famous storm is the Great Red Spot, a huge storm which has been raging since at least 1831.



Jupiter as seen by the Hubble Space Telescope in 2020. Note the bands and the Great Red Spot.
Credits: NASA, ESA, STScI, A. Simon (Goddard Space Flight Center), and M.H. Wong (University of California, Berkeley) and the OPAL team



Close-up of the Great Red Spot taken by the Juno spacecraft in 2017. (Note: the image was rotated by 90° to fit in the slide better.)
Credits: NASA / SwRI / MSSS / Gerald Eichstädt / Seán Doran



Color animation of Jupiter's cloud motion and circulation of the Great Red Spot.
Credits: NASA/JPL/University of Arizona, video URL: https://photojournal.jpl.nasa.gov/catalog/PIA02863

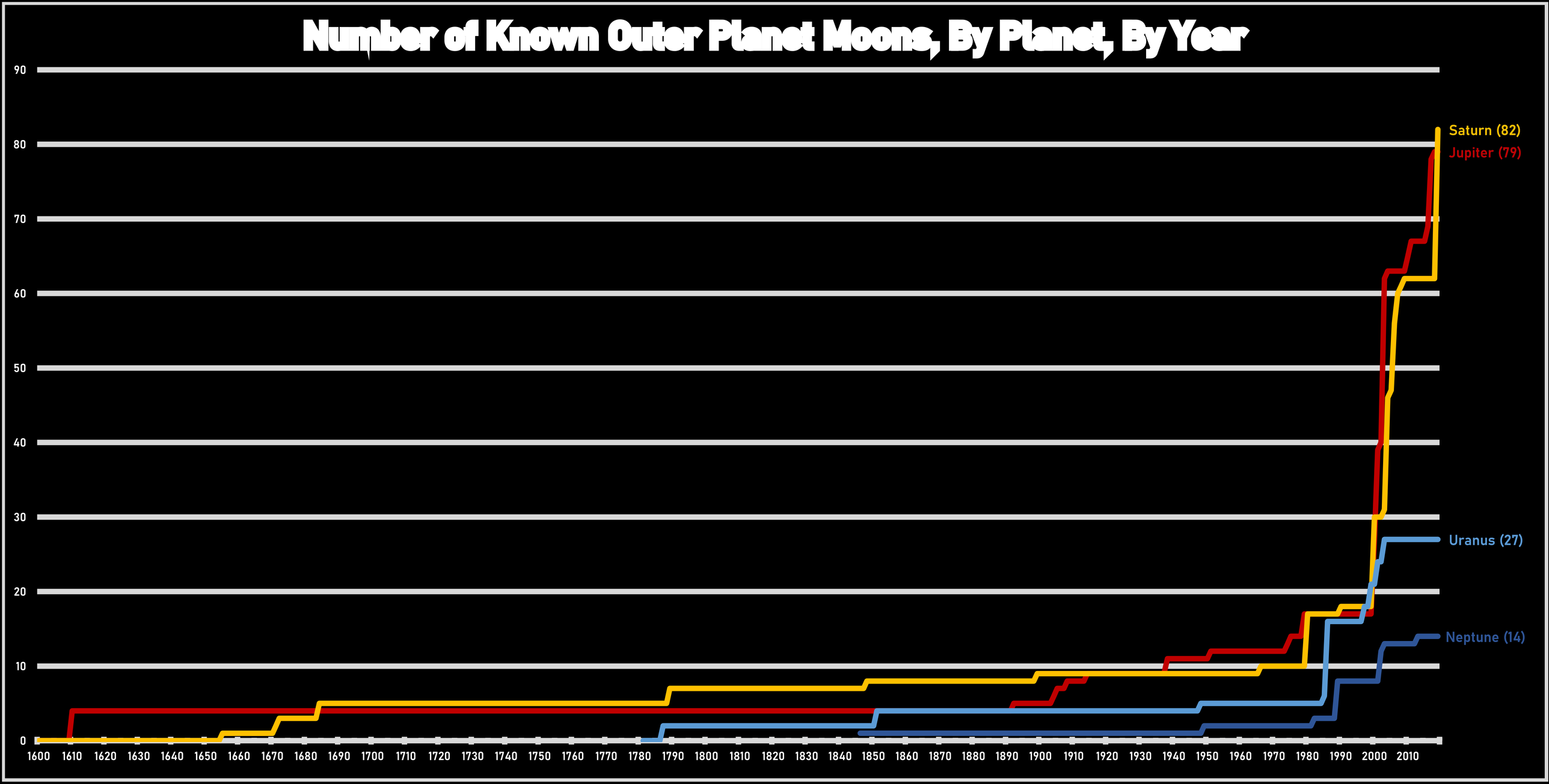
Jupiter

- Jupiter has 80 known moons, and possibly many more. We keep discovering new moons all the time.
- The 4 largest moons are Io, Europa, Ganymede, and Callisto. They were discovered by Galileo in 1610.
- Ganymede is the largest and most massive moon in the solar system: 26% larger than Mercury, but only 45% as massive.

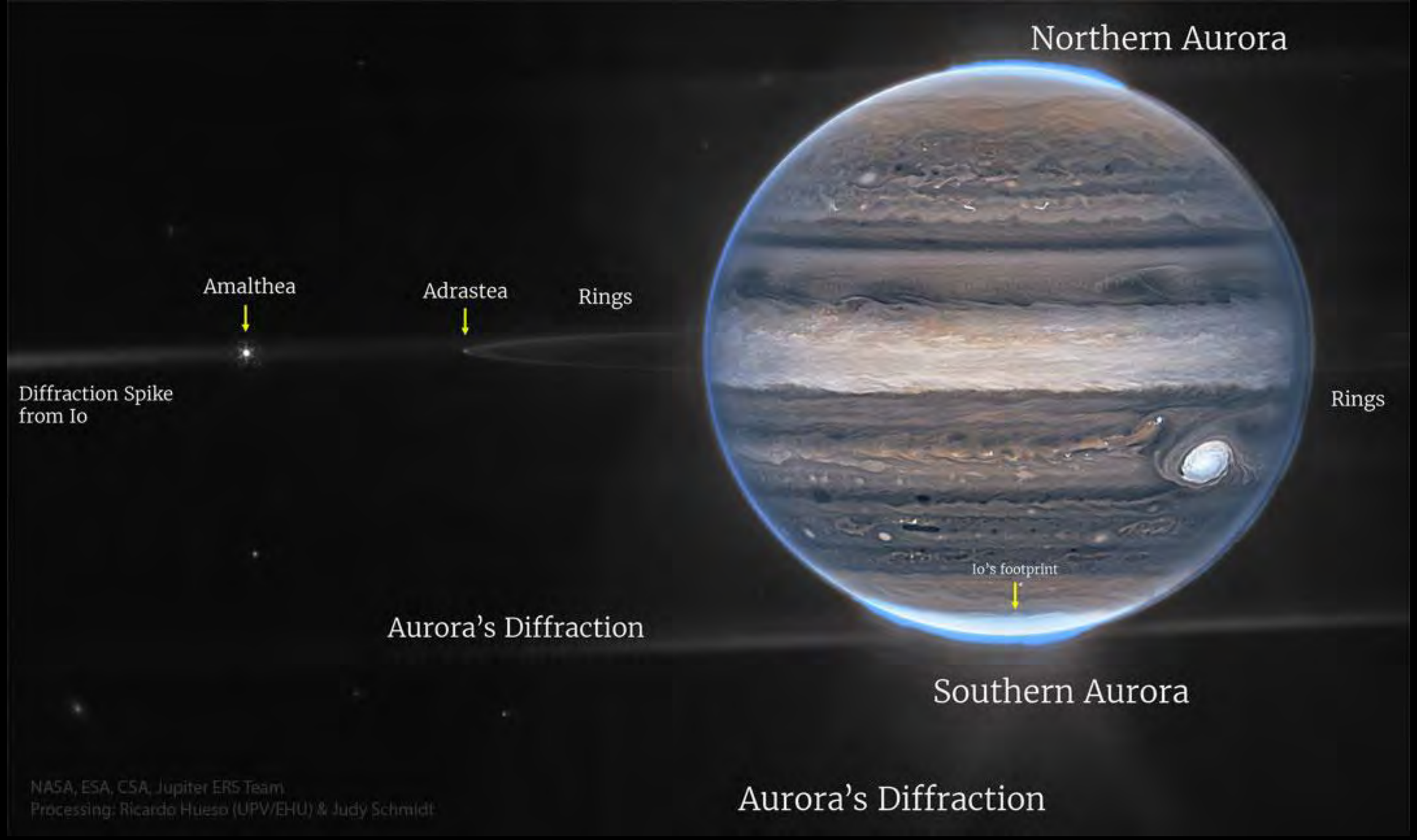
The Galilean moons, as seen by NASA's Galileo spacecraft. From left to right, in order of increasing distance from Jupiter: Io, Europa, Ganymede, and Callisto.
Credits: NASA/JPL/DLR

Jupiter

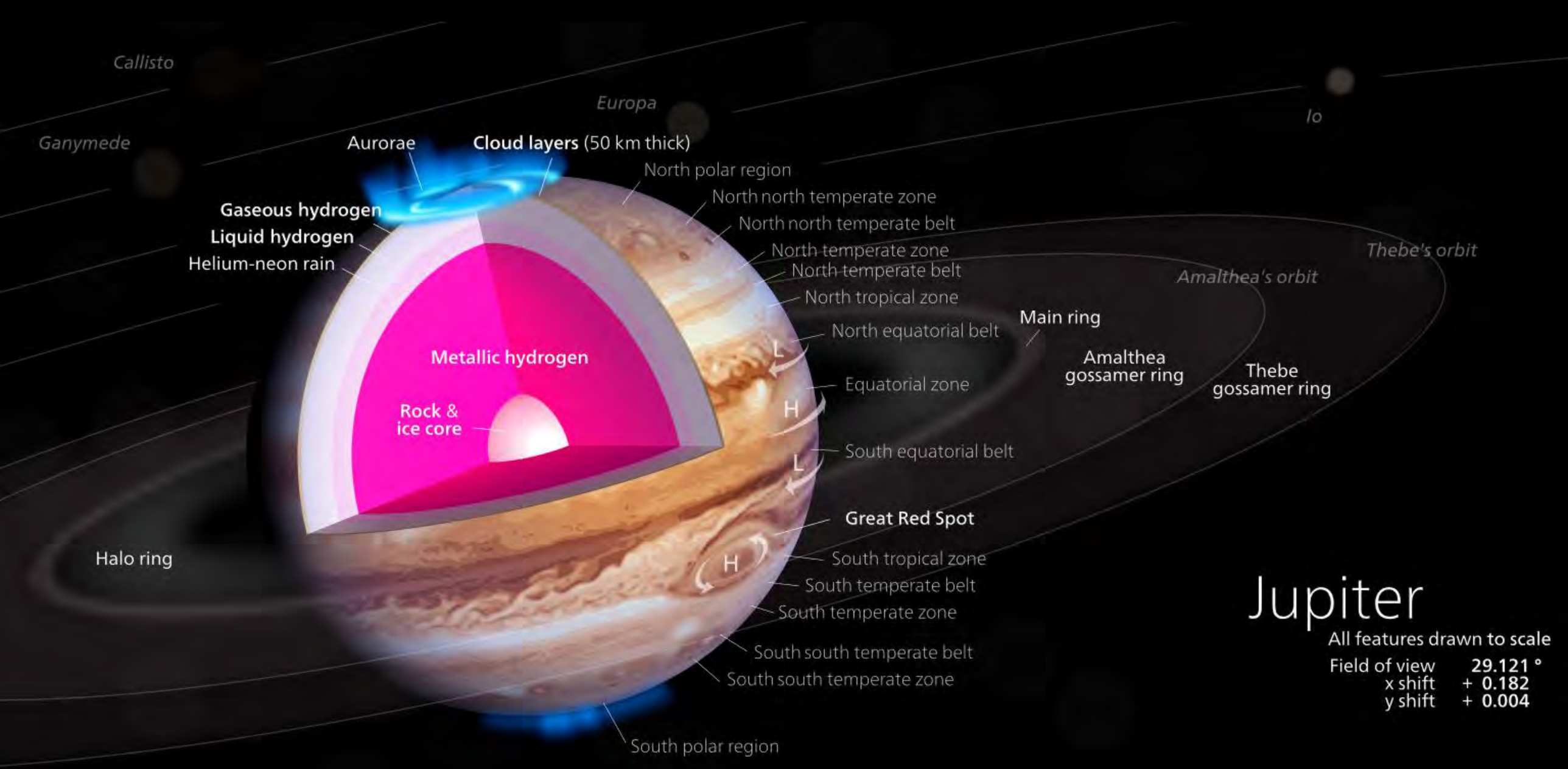
- In general, the outer planets have many more moons than the inner planets.
- Inner: Mercury and Venus have no moons, Earth has 1, Mars has 2.
- Outer: Jupiter has 80+, Saturn has 83+, Uranus has 27+, Neptune has 13+.
- Like all the outer planets, Jupiter also has rings. (However, they are not as impressive as Saturn's rings!)



The number of moons known for each of the outer planets over time.
Credits: StewartIM (Wikipedia)



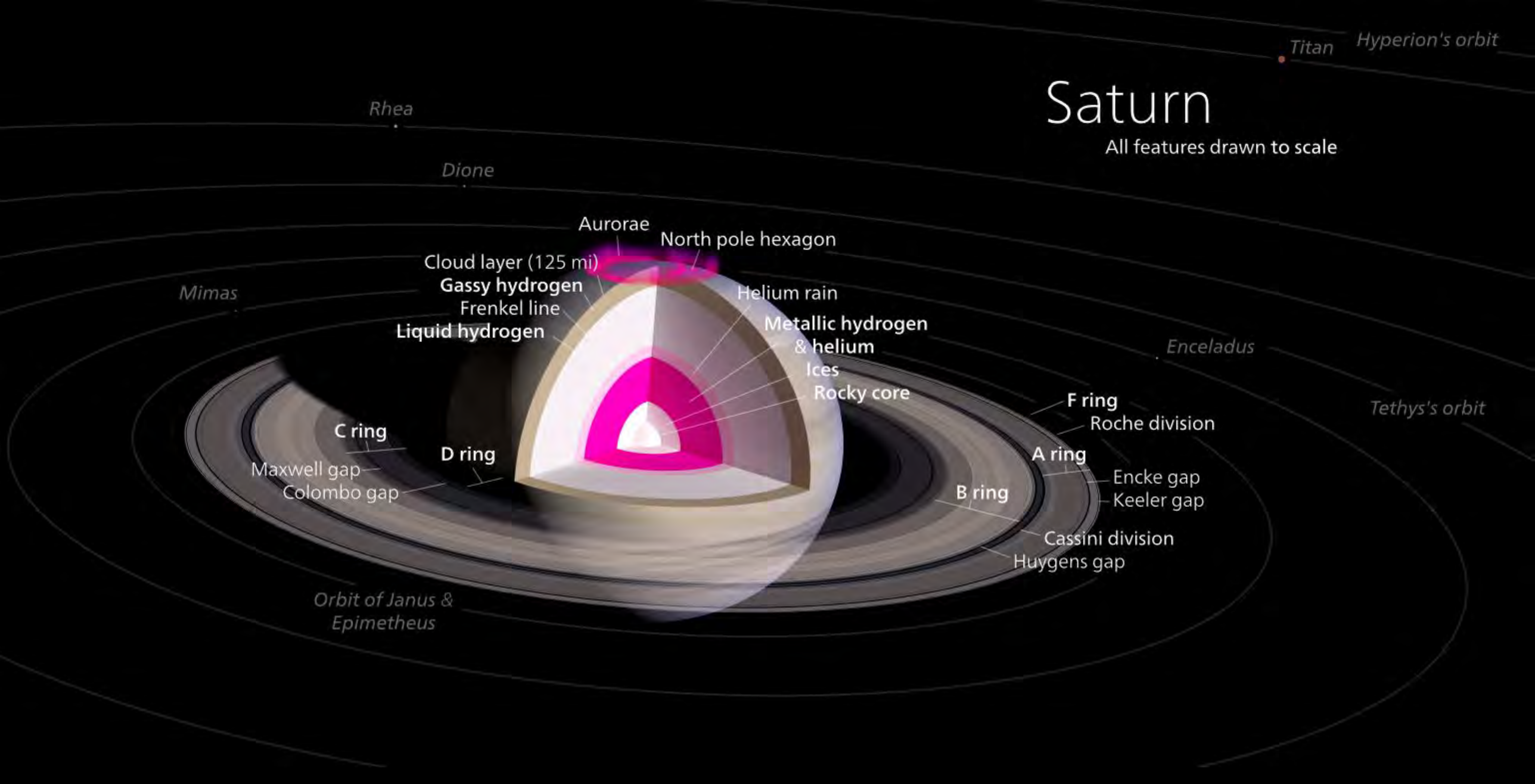
Jupiter as seen in infrared by the James Webb Space Telescope in 2022. Note the rings and the Great Red Spot (which doesn't look red since this is a false-color image).
Credits: NASA, ESA, CSA, Jupiter ERS Team; Processing: Ricardo Hueso (UPV/EHU) & Judy Schmidt



The structure of Jupiter. Note that the core and the layer of liquid metallic hydrogen (a phase of hydrogen that can conduct electricity) are hypothetical.
Credits: StewartIM (Wikipedia)

Saturn

- Saturn is the sixth planet from the Sun.
- Its semi-major axis is ~1.4 billion km or ~9.6 AU.
- Its internal structure is similar to that of Jupiter. From innermost to outermost:
  - A core of iron-nickel and rock.
  - A deep layer of metallic hydrogen.
  - An intermediate layer of liquid hydrogen and liquid helium.
  - A gaseous outer layer.



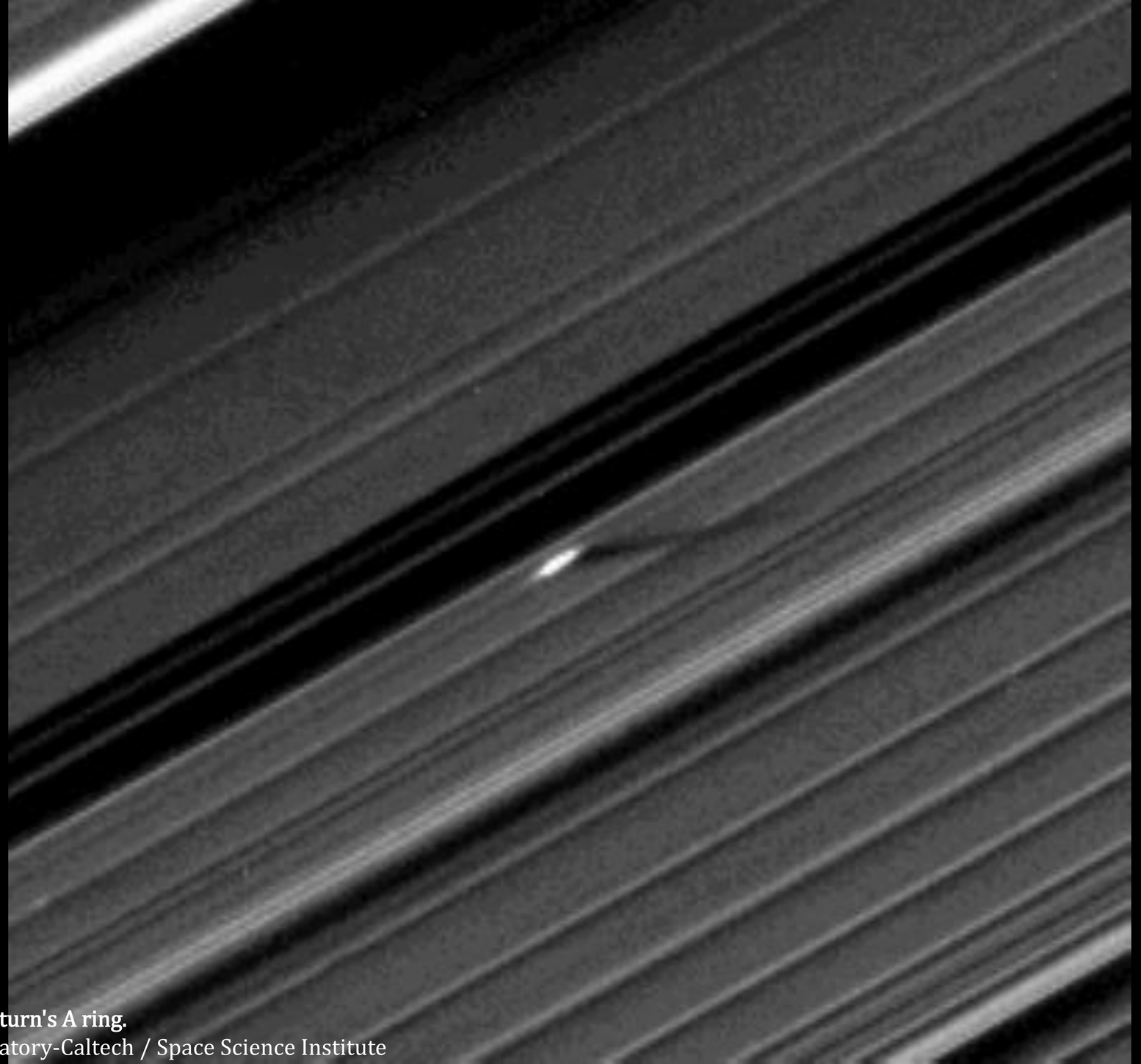
The structure of Saturn.
Credits: Kelvinsong (Wikipedia)

Saturn

- Saturn appears pale yellow due to ammonia crystals in its upper atmosphere.
- It has 83 known moons.
- Saturn’s most famous feature is its ring system, composed mainly of ice particles, with some rocky debris and dust.
- There are hundreds of moonlets (small moons) orbiting inside the rings.
- The 7 main rings are labeled in letters from A to G in the order of discovery.

An artist's concept of Saturn's rings and major icy moons. The diffuse E ring extends from Mimas' orbit to Titan's orbit, about 1 million km.
Credits: NASA/JPL

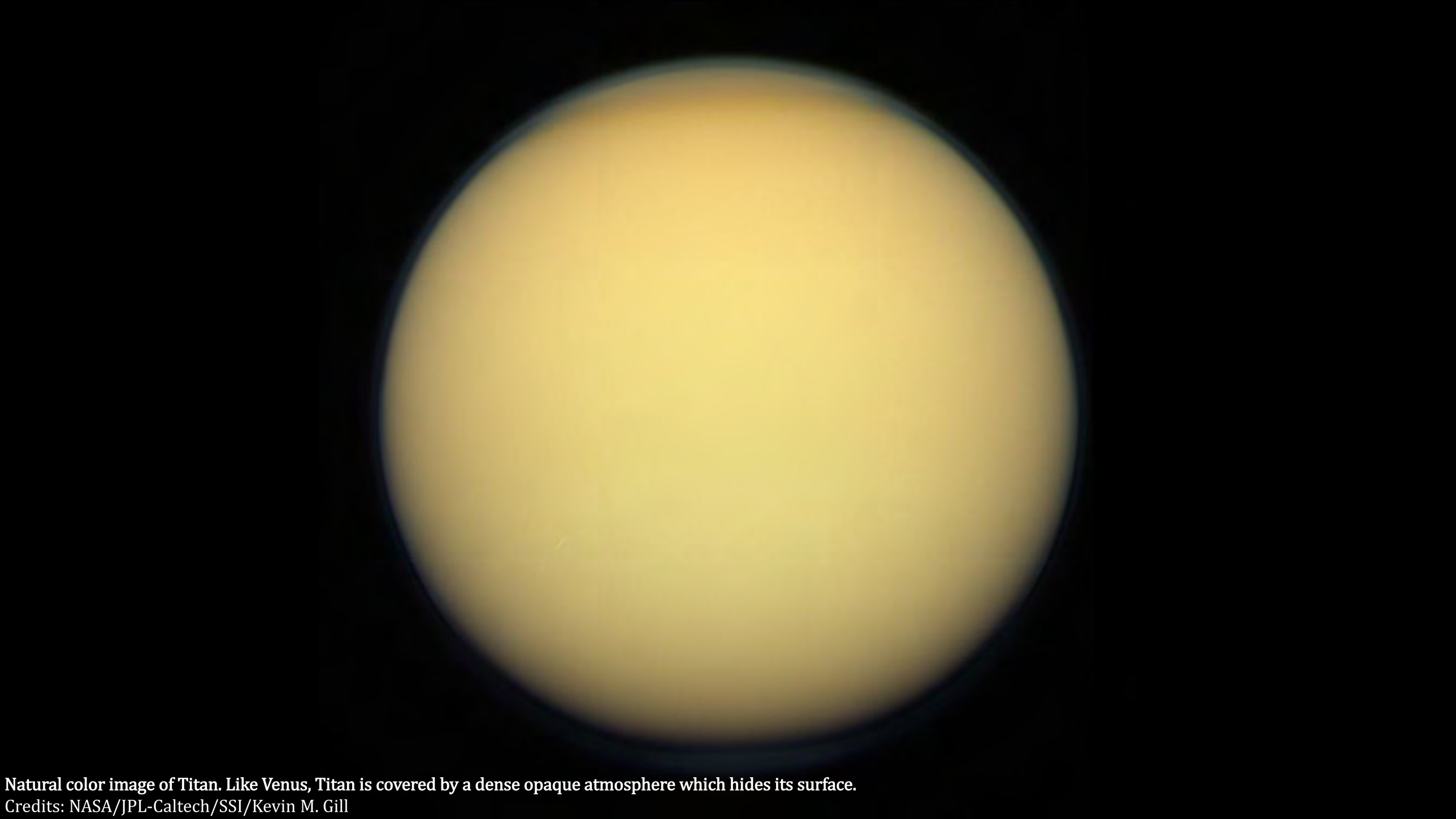
Natural color view of the outer C ring and B ring, as captured in 2009 by NASA's Cassini spacecraft.
Credits: NASA / Jet Propulsion Laboratory-Caltech / Space Science Institute



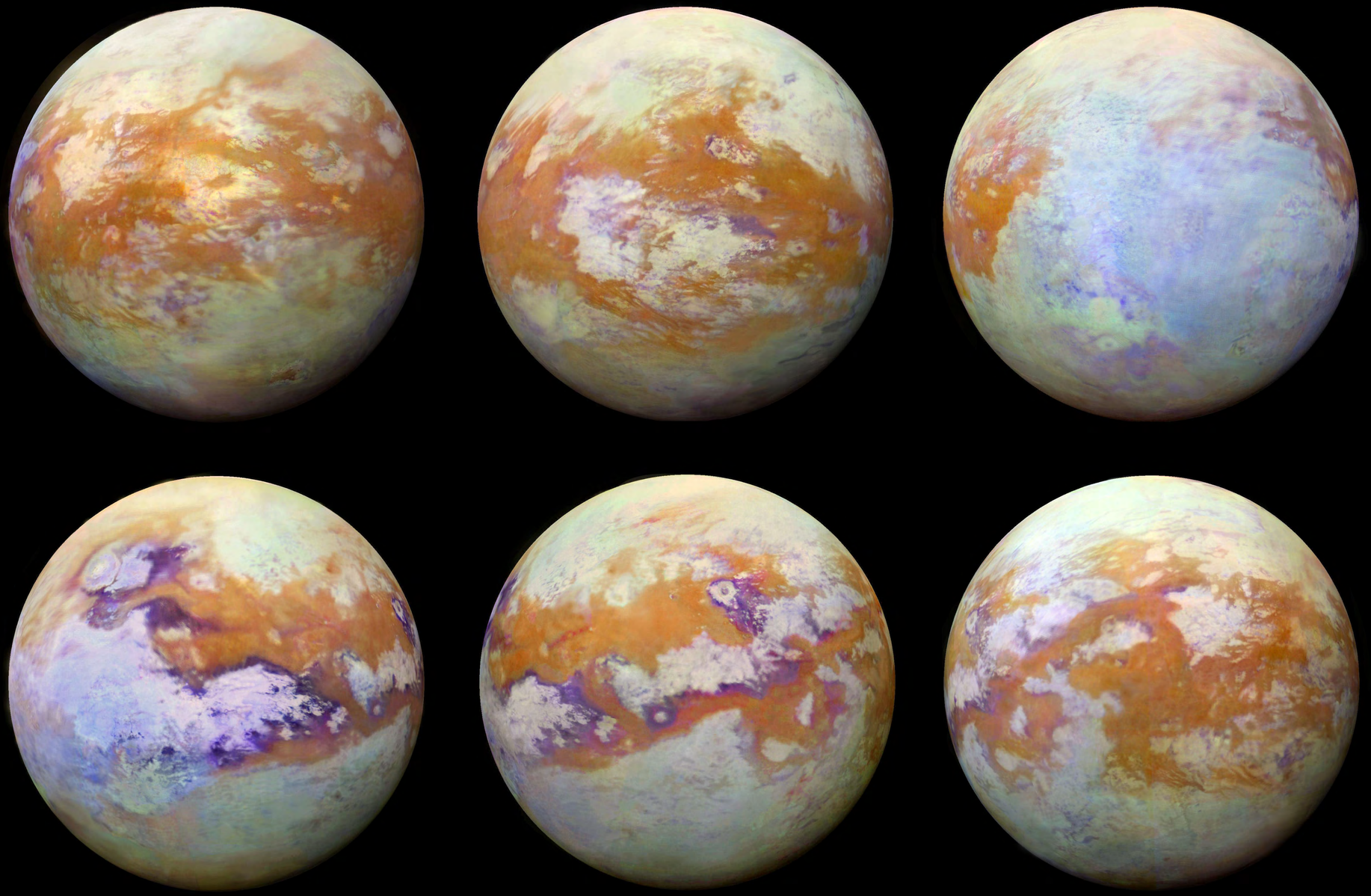
The 400-meter moonlet Earhart in Saturn's A ring.
Credits: NASA / Jet Propulsion Laboratory-Caltech / Space Science Institute

Saturn

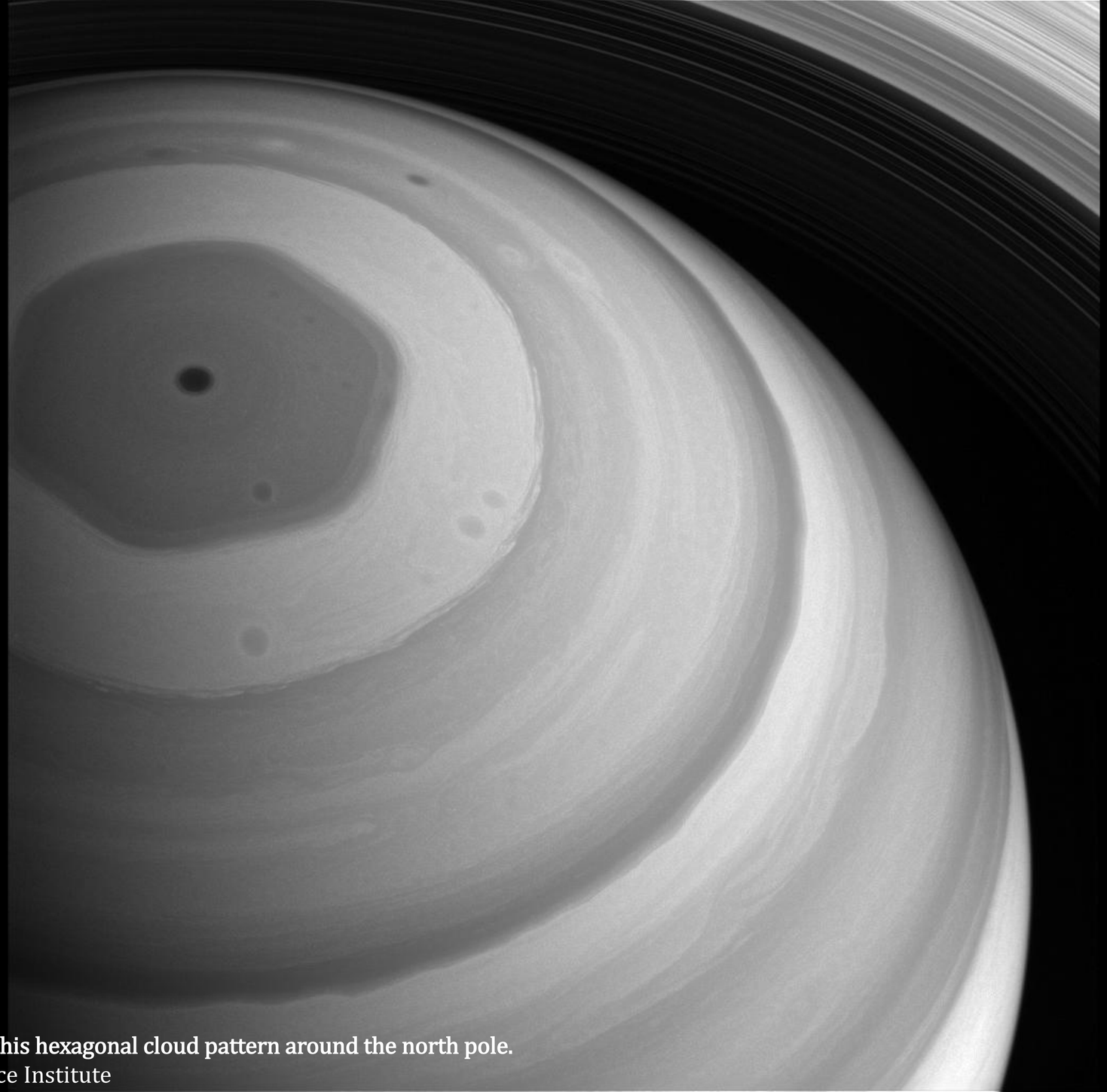
- Saturn’s largest moon, Titan, is the second-largest in the solar system (after Ganymede).
- Titan is also the only moon in the solar system with a substantial atmosphere. It is composed largely of nitrogen.
- It is the only known object other than Earth with evidence of stable bodies of surface liquid.
- Titan is primarily composed of ice and rocks, likely differentiated into a rocky core surrounded by various layers of ice.
- It also has a crust of ice and a subsurface layer of ammonia-rich liquid water.



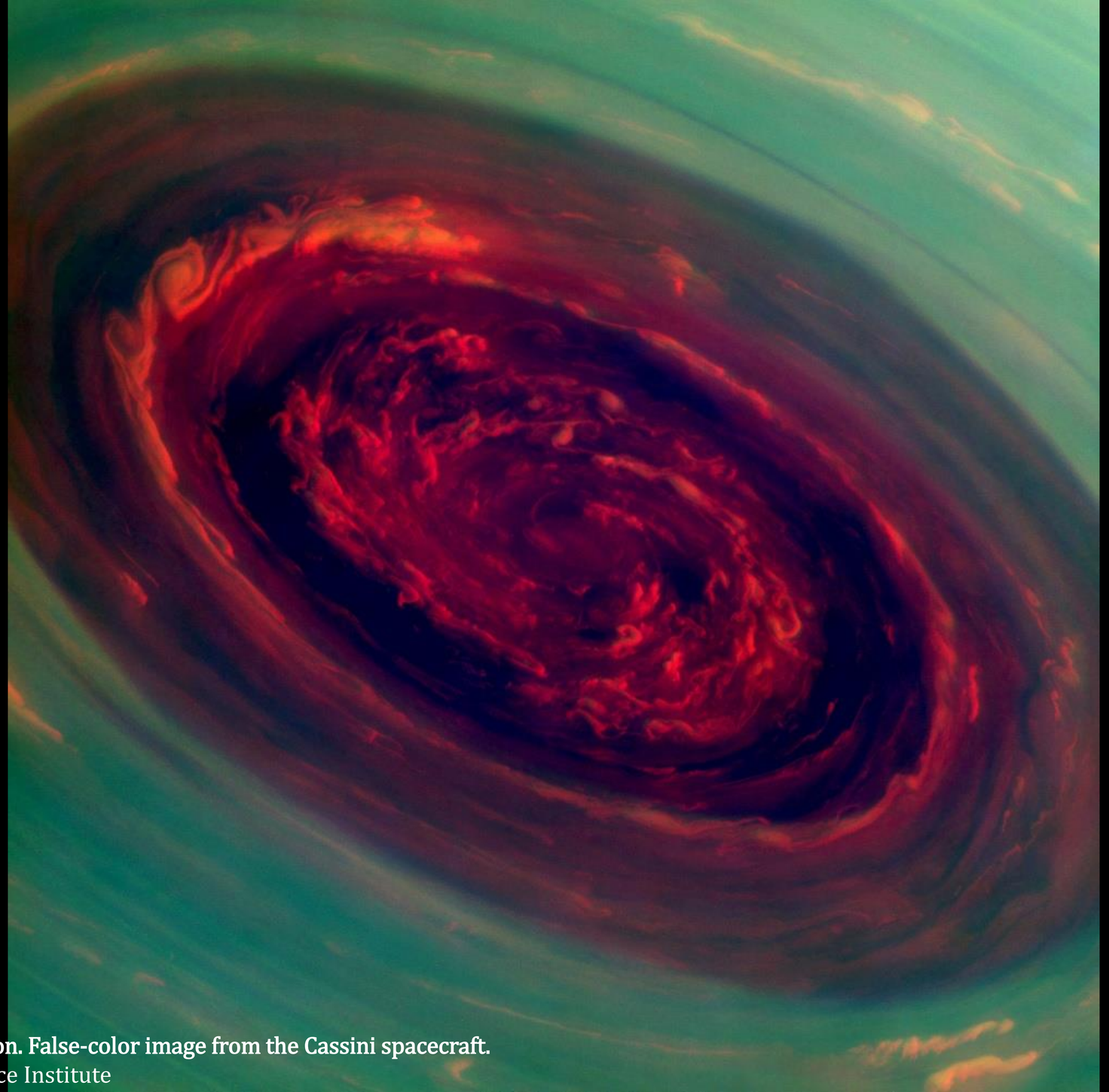
Natural color image of Titan. Like Venus, Titan is covered by a dense opaque atmosphere which hides its surface.
Credits: NASA/JPL-Caltech/SSI/Kevin M. Gill



Infrared images of Titan, showing its surface.
Credits: NASA/JPL-Caltech/SSI/Kevin M. Gill



Another interesting feature of Saturn is this hexagonal cloud pattern around the north pole.
Credits: NASA/JPL-Caltech/Space Science Institute



A huge spinning vortex inside the hexagon. False-color image from the Cassini spacecraft.
Credits: NASA/JPL-Caltech/Space Science Institute

Uranus

- Uranus is the seventh planet from the Sun.
- Its semi-major axis is ~2.9 billion km or ~19 AU.
- There are two ways to pronounce its name:
  1. YOOR-a-nes (seems to be preferred among astronomers)
  2. yoo-RAY-nes

Uranus

- Uranus can be seen with the naked eye. However, it is very dim and moves slowly across the sky (its orbital period is 84 Earth years).
- Therefore, it was long thought to be one of the fixed stars.
  - Recall: planets are “wandering stars”, because they move in the sky.
- In 1781, William Herschel observed Uranus with a telescope and realized it wasn’t a fixed star, because it was moving. But he initially thought it was a comet.
- Astronomers computed its orbit and found that it is nearly circular. Since most comets have very eccentric paths, they concluded Uranus is most likely a planet.

Uranus

- Both Uranus and Neptune are ice giants. This is different from Jupiter and Saturn, which are gas giants.
- Gas giants are composed mainly of hydrogen and helium.
- Ice giants are composed mainly of heavier elements such as oxygen, carbon, nitrogen, and sulfur.
- None of the giants have solid surfaces.

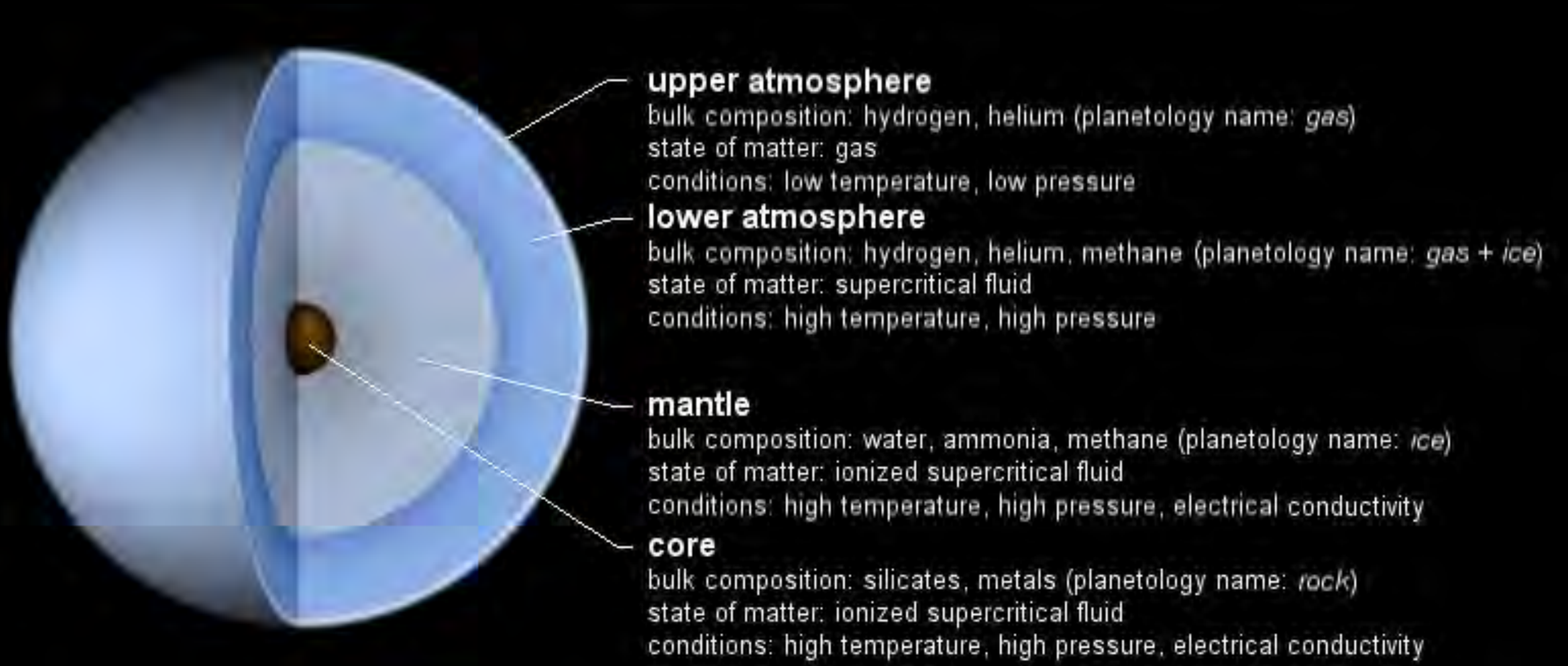
Uranus

- In astronomy, the word “ice” doesn’t mean the substance is solid or cold, like water ice.
- “Gases” have extremely low melting points. For example:
  - Hydrogen (H): ~14 K (−259 °C)
  - Helium (He): ~1 K (−272 °C)
- “Ices” have melting points above ~90 K (–173 °C). For example:
  - Water (H_2O): ~273 K (0 °C)
  - Ammonia (NH_3): ~195 K (−78 °C)
  - Methane (CH_4): ~91 K (−182 °C)
- “Ices” in ice giants are generally in liquid or gas form, and very hot!

Uranus

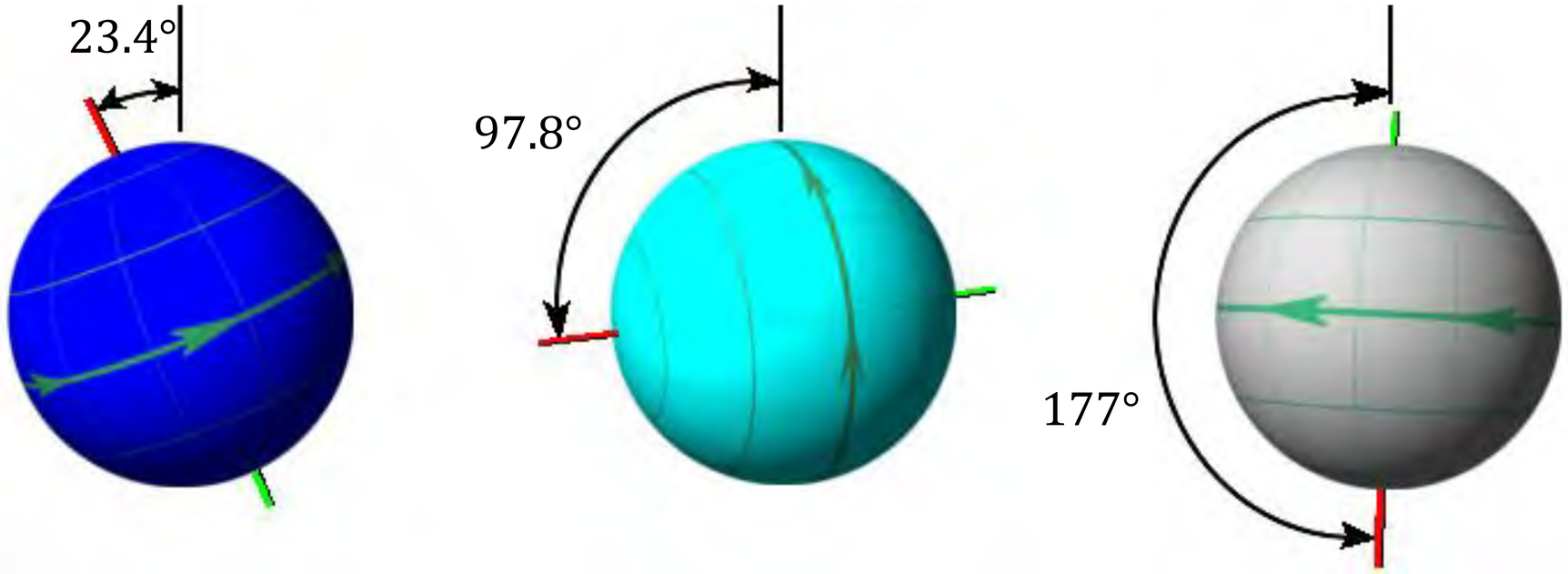
- The interior of Uranus is mainly composed of ices and rocks.
- It has a layered cloud structure, with a lower layer of water clouds and an upper layer of methane clouds.
- Uranus appears blue due to the methane it contains.

True-color image of Uranus as seen by NASA's Voyager 2 spacecraft in 1986.
Credits: NASA



The interior structure of Uranus.
Credits: FrancescoA / WolfmanSF (Wikipedia)

- Uranus is unique in the solar system, because its spin axis is tilted sideways compared to its axis of revolution around the Sun.
- Its axial tilt is ~97.8°, close to a right angle of 90°.
- Thus, its north pole points toward the Sun, rather than upward.

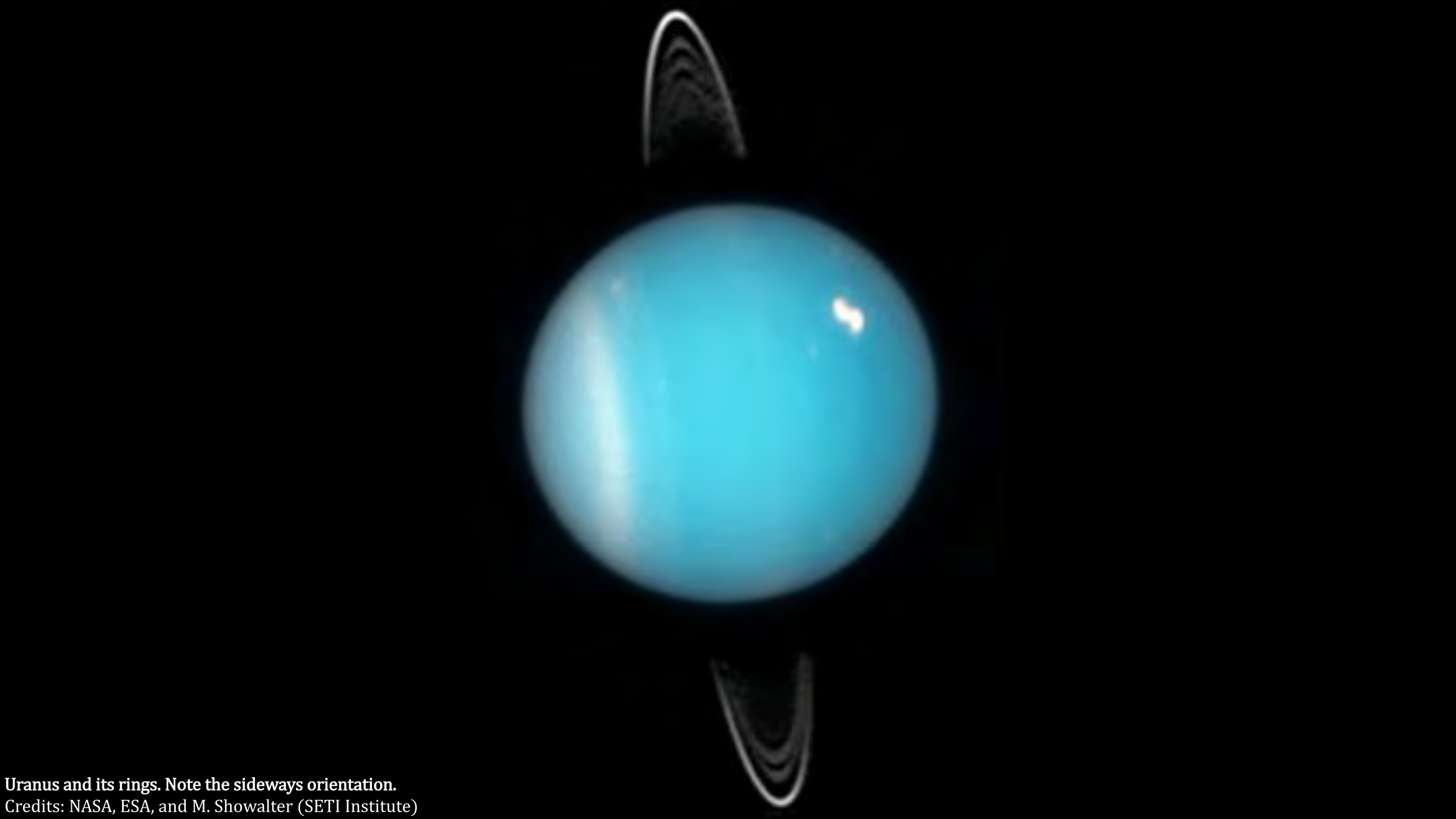


Earth Uranus Venus

Credits: Modification of work by Tfr000 (Wikipedia)

Uranus

- This tilt was likely caused by a collision with another large celestial body, which turned the planet “on its side”.
- Like the other giants, Uranus has a ring system (with 13 rings) and many moons (27 currently known).
- These rings and moons rotate around the equator of Uranus, which means they also rotate perpendicular to the rest of the solar system.



Uranus and its rings. Note the sideways orientation.
Credits: NASA, ESA, and M. Showalter (SETI Institute)

Uranus

- Since Uranus is tilted sideways, it experiences seasons very differently from other planets.
- Recall: a solstice is when the Sun is highest or lowest in the sky.
- Near the solstices on Uranus ("summer" and "winter"):
  - One pole faces the Sun continuously and the other faces away.
  - A narrow strip around the equator experiences a rapid day–night cycle, with the Sun low over the horizon.
- You can imagine the planet "rolling on its side" along its orbit. (Most planets move along their orbits like spinning tops.)

Uranus and its 6 largest moons. Sizes to scale, distances not to scale. From right to left: Puck, Miranda, Ariel, Umbriel, Titania, and Oberon.
Credits: NASA

Neptune

- Neptune is the eighth planet from the Sun and the farthest known planet in the solar system.
- Its semi-major axis is ~4.5 billion km or ~30 AU.
- Since light intensity decreases as the square of the distance, sunlight on Neptune (30 AU) is $30^2 = 900$ times weaker than sunlight on Earth (1 AU).
- It also has the longest orbital period: ~165 years.

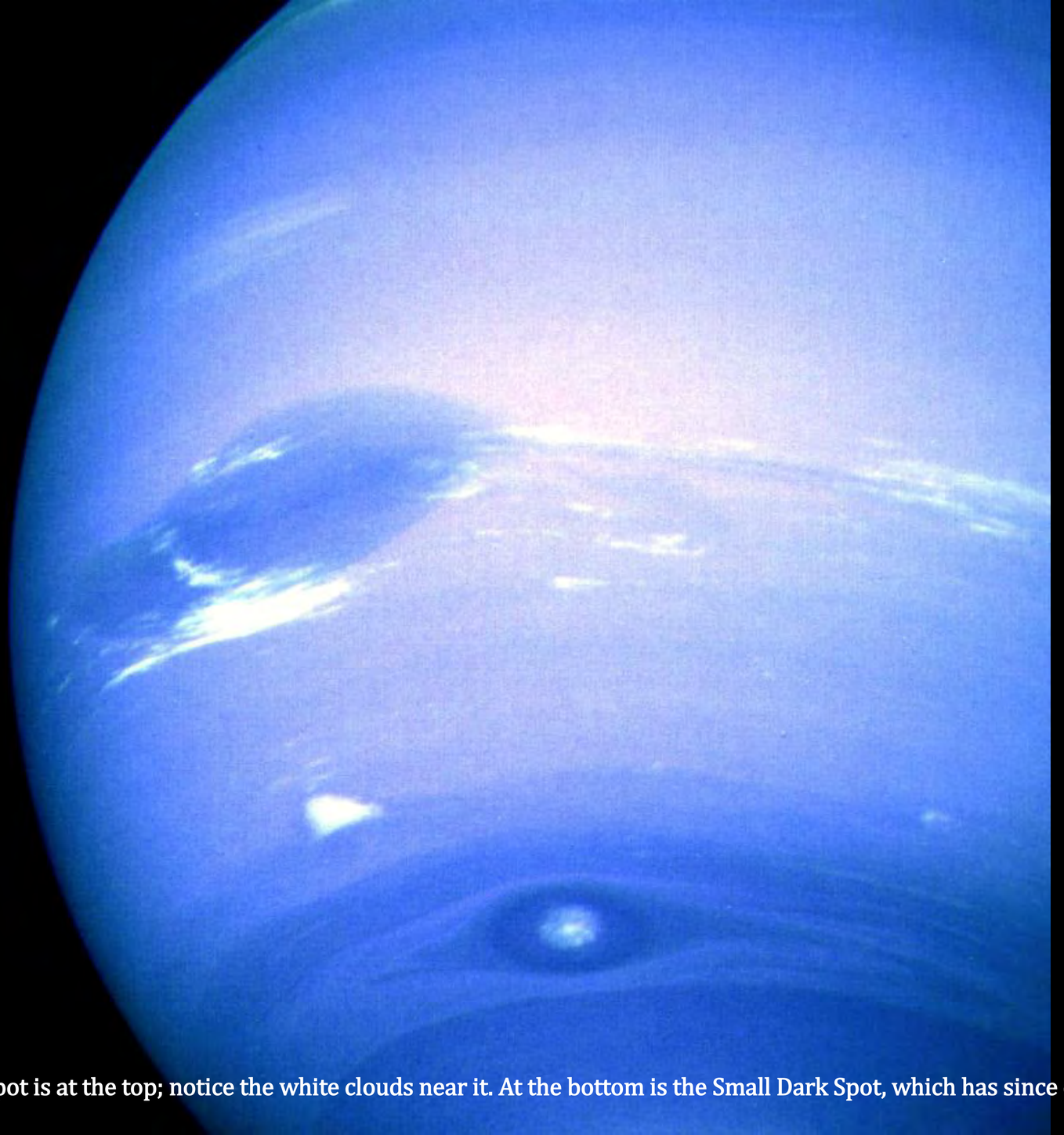
Neptune

- Neptune is the only planet that cannot be seen with the naked eye.
- In fact, Neptune was initially discovered mathematically, rather than by direct observation.
- The orbit of Uranus was not behaving as Newtonian physics predicted.
- This led astronomers to think there must be another planet exerting its gravitational force on Uranus and changing its orbit.
- They were able to calculate where this planet, Neptune, must be located, and observed it there with a telescope in 1846.

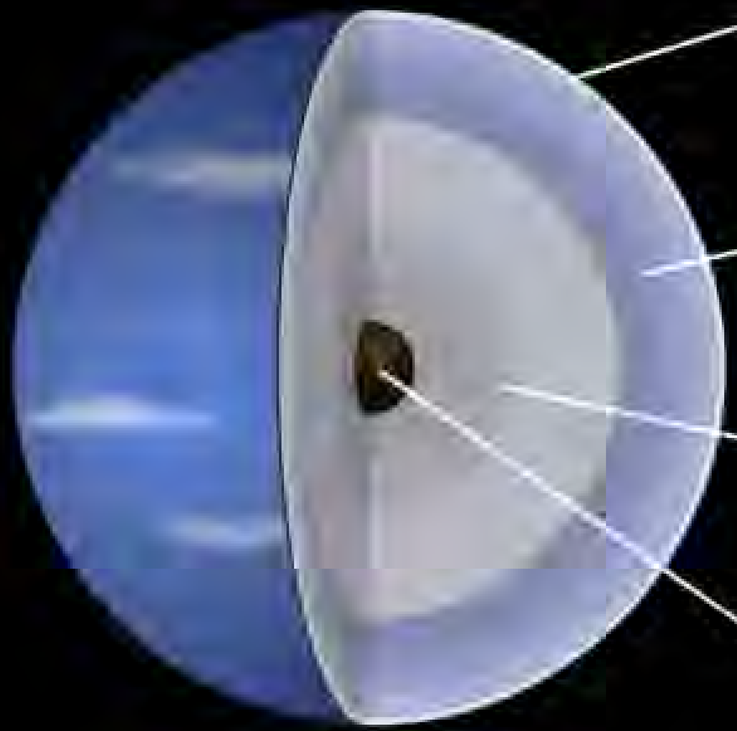
Neptune

- Neptune is also an ice giant, like Uranus, and its interior is primarily composed of ices and rock.
- Also like Uranus, it is blue due to the methane in its outer regions.
- However, unlike Uranus, Neptune has visible weather patterns.
- The most famous example is the Great Dark Spot, similar to the Great Red Spot on Jupiter.
- Neptune also has the strongest winds of any planet in the solar system, with wind speeds as high as 2,100 km/h.

Neptune as seen by NASA's Voyager 2 spacecraft in 1989. Note the Great Dark Spot at the center.
Credits: NASA / JPL / Voyager-ISS / Justin Cowart



A close-up of Neptune by Voyager 2. The Great Dark Spot is at the top; notice the white clouds near it. At the bottom is the Small Dark Spot, which has since disappeared
Credits: NASA / JPL / Voyager-ISS / Justin Cowart



upper atmosphere
bulk composition: hydrogen, helium (planetology name: *gas*)
state of matter: gas
conditions: low temperature, low pressure

lower atmosphere
bulk composition: hydrogen, helium, methane (planetology name: *gas + ice*)
state of matter: supercritical fluid
conditions: high temperature, high pressure

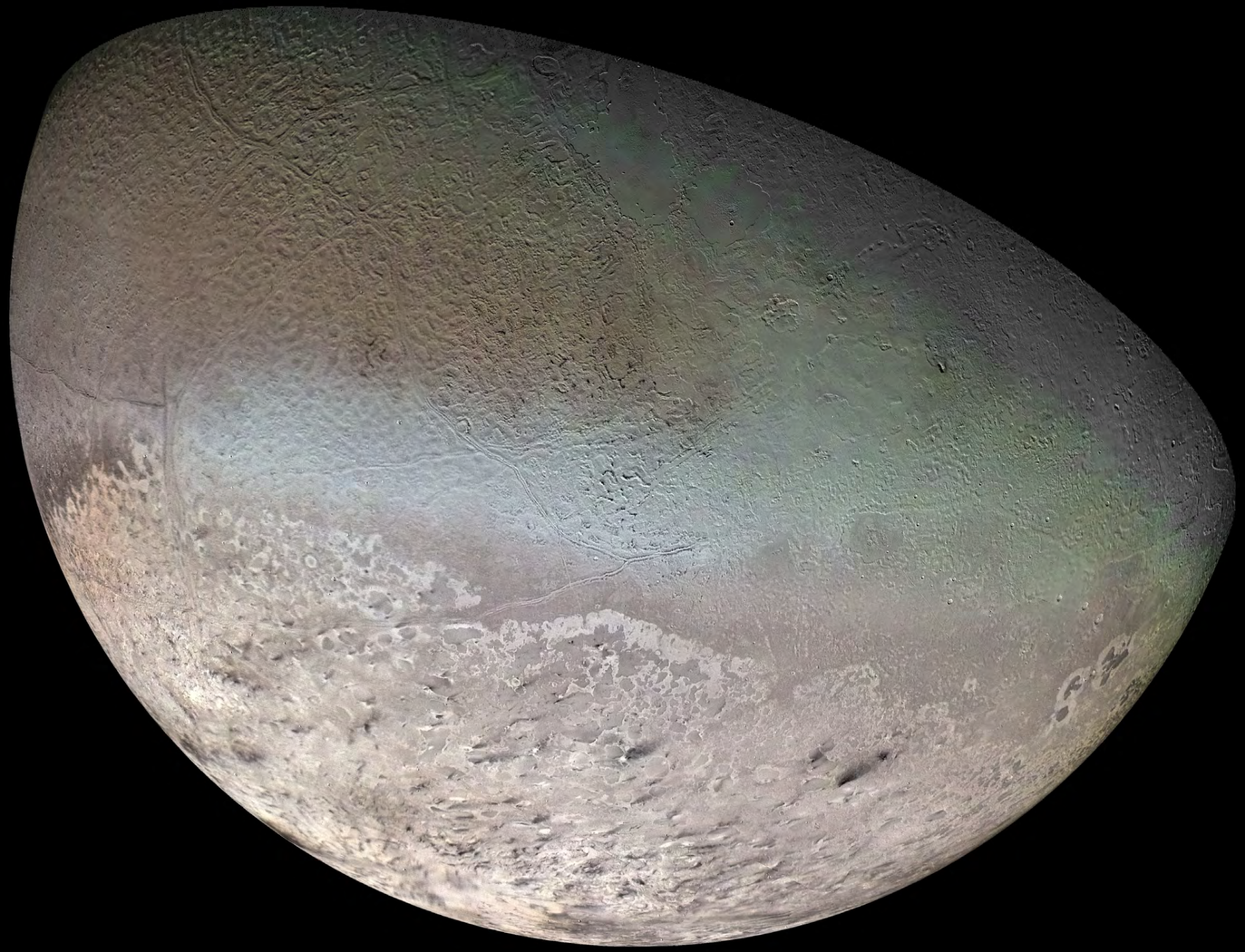
mantle
bulk composition: water, ammonia, methane (planetology name: *ice*)
state of matter: ionized supercritical fluid
conditions: high temperature, high pressure, electrical conductivity

core
bulk composition: silicates, metals (planetology name: *rock*)
state of matter: ionized supercritical fluid
conditions: high temperature, high pressure, electrical conductivity

The interior structure of Neptune.
Credits: Lajoswinkler (Wikipedia)

Neptune

- Neptune has 14 known moons.
- Its largest moon is Triton, discovered only 17 days after the discovery of Neptune itself.
  - Triton is the only large moon in the solar system with a retrograde orbit, opposite to Neptune's rotation.
  - Because of that, it is thought to have been a dwarf planet captured from the Kuiper belt.
- It took over a century before another moon, Nereid (NEER-ee-id), was discovered.
- Like the other giant planets, Neptune also has rings.



Triton, Neptune's largest moon, as seen by Voyager 2 in 1989.
Credits: NASA / Jet Propulsion Lab / U.S. Geological Survey

Neptune as seen in infrared by the James Webb Space Telescope in 2022. Note the rings and 6 moons around it. The bright patches are methane clouds.
Credits: NASA, ESA, CSA, STScI

Pluto

- Pluto is a dwarf planet.
- Pluto was discovered in 1930, and was considered the ninth planet from the Sun for a long time.
- However, with time, many more similar objects were discovered in the same region, now known as the Kuiper (KIE-per) belt.
- The Kuiper belt extends from the orbit of Neptune, at ~30 AU, all the way up to ~50 AU.

Pluto

- In 2006, the International Astronomical Union (IAU) defined a planet as any object that:
  1. Is in direct orbit around the Sun (not around another object).
  2. Is massive enough to be rounded by its own gravity.
  3. "Clears the neighborhood" around its orbit, sweeping out smaller bodies over time until it does not share its orbit with any other bodies of comparable size (except its own moons).
- A dwarf planet is an object that satisfies criteria 1 and 2 but not 3.
- Since Pluto didn't clear its neighborhood (it shares it with other Kuiper belt objects), it was reclassified as a dwarf planet.

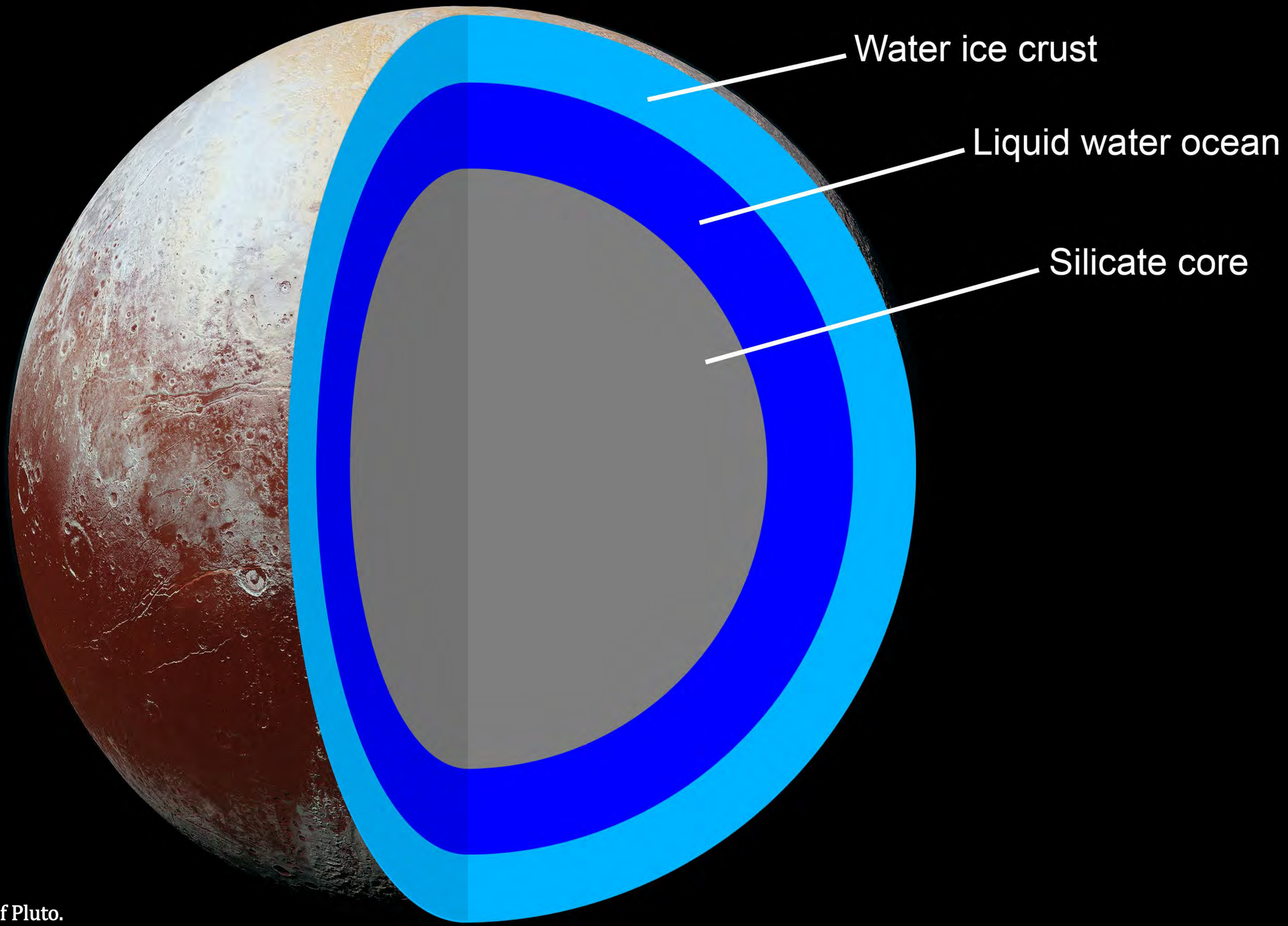
Pluto

- This redefinition of Pluto in 2006 sparked a great public debate.
- People were upset that Pluto was “downgraded” to a dwarf planet.
- New Mexico and Illinois even passed resolutions that declared Pluto to be considered a planet in those states (because Pluto’s discoverer, Clyde Tombaugh, lived there).
- In reality, Pluto being reclassified as a dwarf planet doesn’t mean it’s any less “important” than it was before. It just means we understand the universe better now, so we can give more precise and useful definitions to things.

Pluto as seen by NASA's New Horizons spacecraft in 2015.
Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Alex Parker

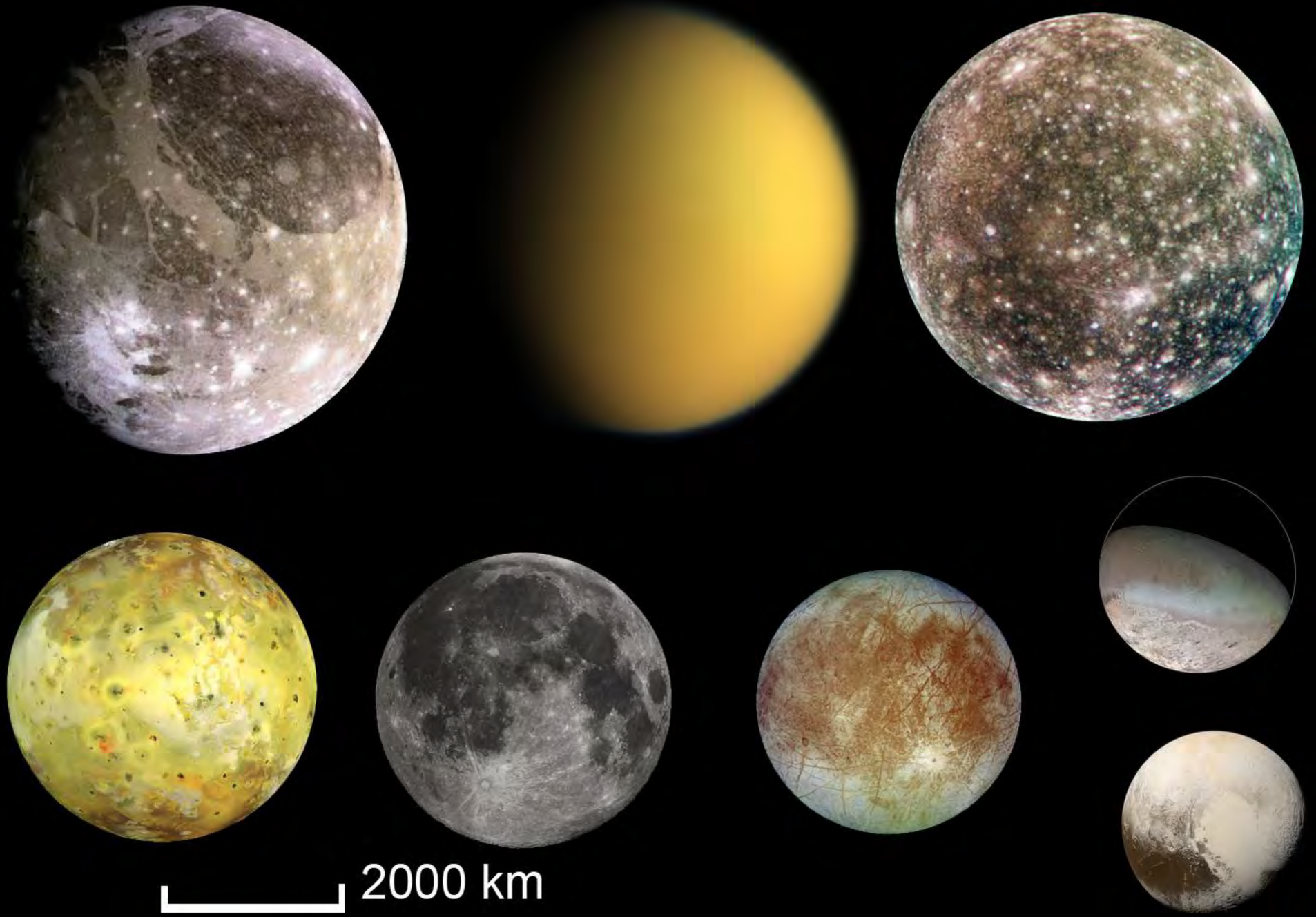
Pluto

- Pluto is made primarily of ice and rock, and is much smaller than the inner planets.
- Other Kuiper belt objects have similar composition and size.
- Pluto has 1/6 the mass and 1/3 the volume of Earth's Moon. It is smaller than many of the larger moons in the solar system.
- Pluto has 5 known moons: Charon (the largest), Styx, Nix, Kerberos, and Hydra.

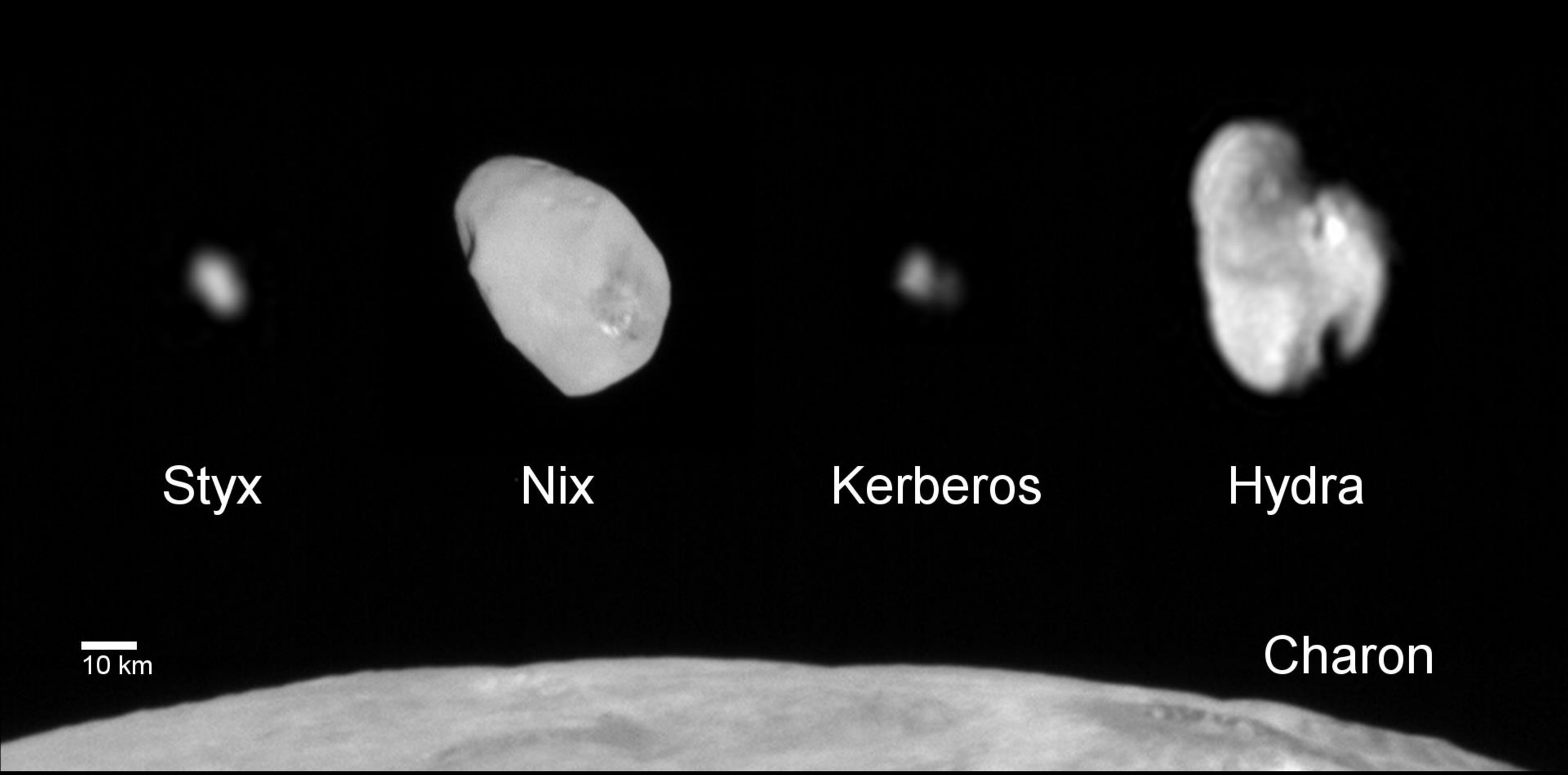


The internal structure of Pluto.
Credits: PlanetUser (Wikipedia)

Size comparison: Earth (right), Earth's Moon (top left), Pluto (bottom left).
Credits: NASA; Gregory H. Revera; NASA/JHUAPL/SWRI



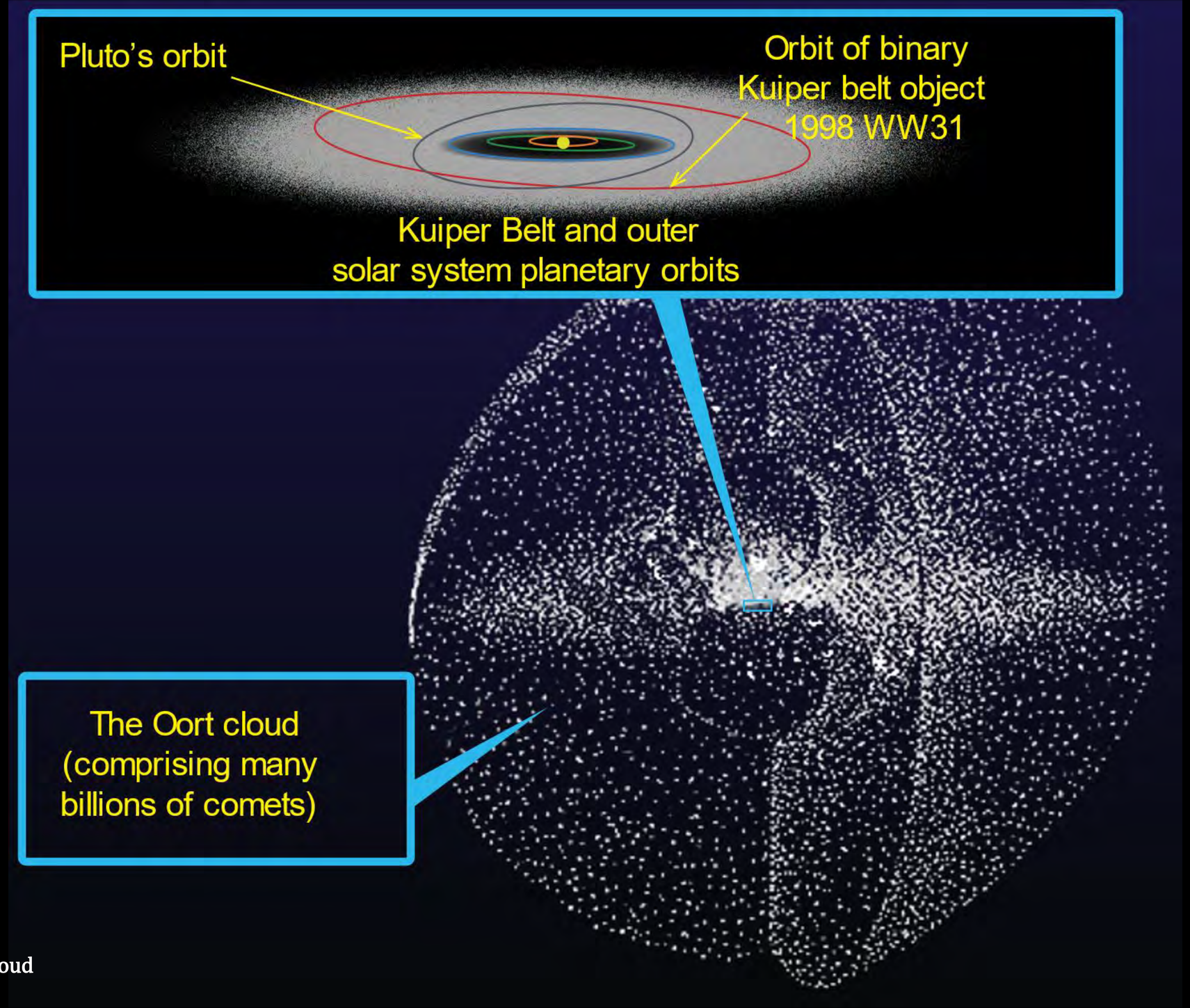
Pluto vs. the largest moons. Left to right: top – Ganymede (Jupiter), Titan (Saturn), Callisto (Jupiter); bottom – Io (Jupiter), Moon (Earth), Europa (Jupiter), Triton (Neptune), Pluto.
Credits: NASA



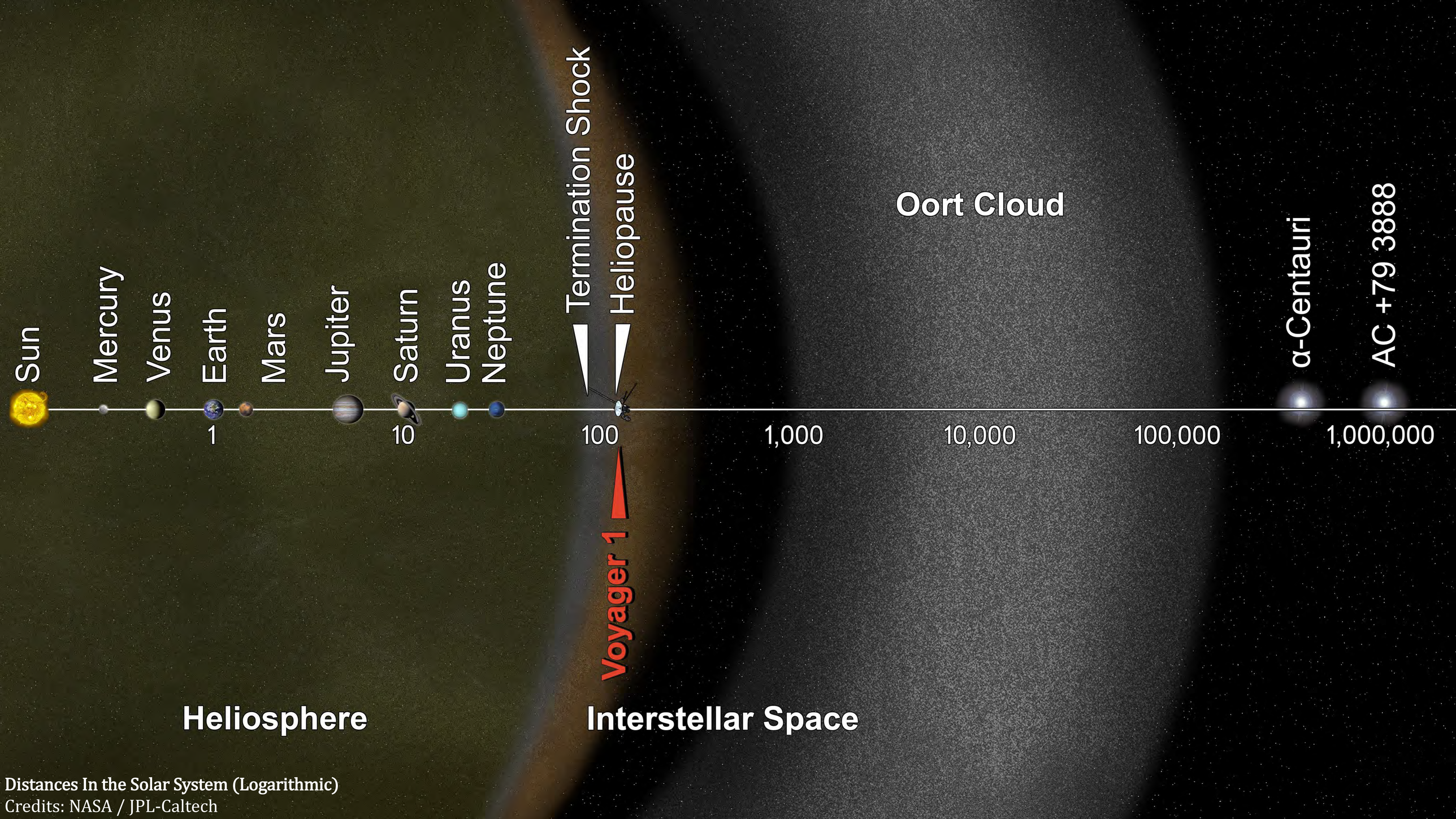
Pluto’s 5 known moons. Charon is at the bottom, mostly out of frame.
Credits: NASA/JHUAPL/SwRI

Pluto

- Trans-Neptunian objects (TNOs) are any planet-like objects, including dwarf planets, that are beyond the orbit of Neptune.
- Pluto was the first TNO to be discovered, and there are more than 2,600 other TNOs currently known.
- Some TNOs have moons of their own, and at least one, the dwarf planet Haumea, is known to have rings.
- Trans-Neptunian objects also exist beyond the Kuiper belt, even all the way out to the Oort (OR-t) cloud, at 2,000 to 200,000 AU (3.2 light-years) from the Sun.
  - These are sometimes called extreme trans-Neptunian objects (ETNOs).



The Kuiper Belt and the Oort Cloud
Credits: NASA

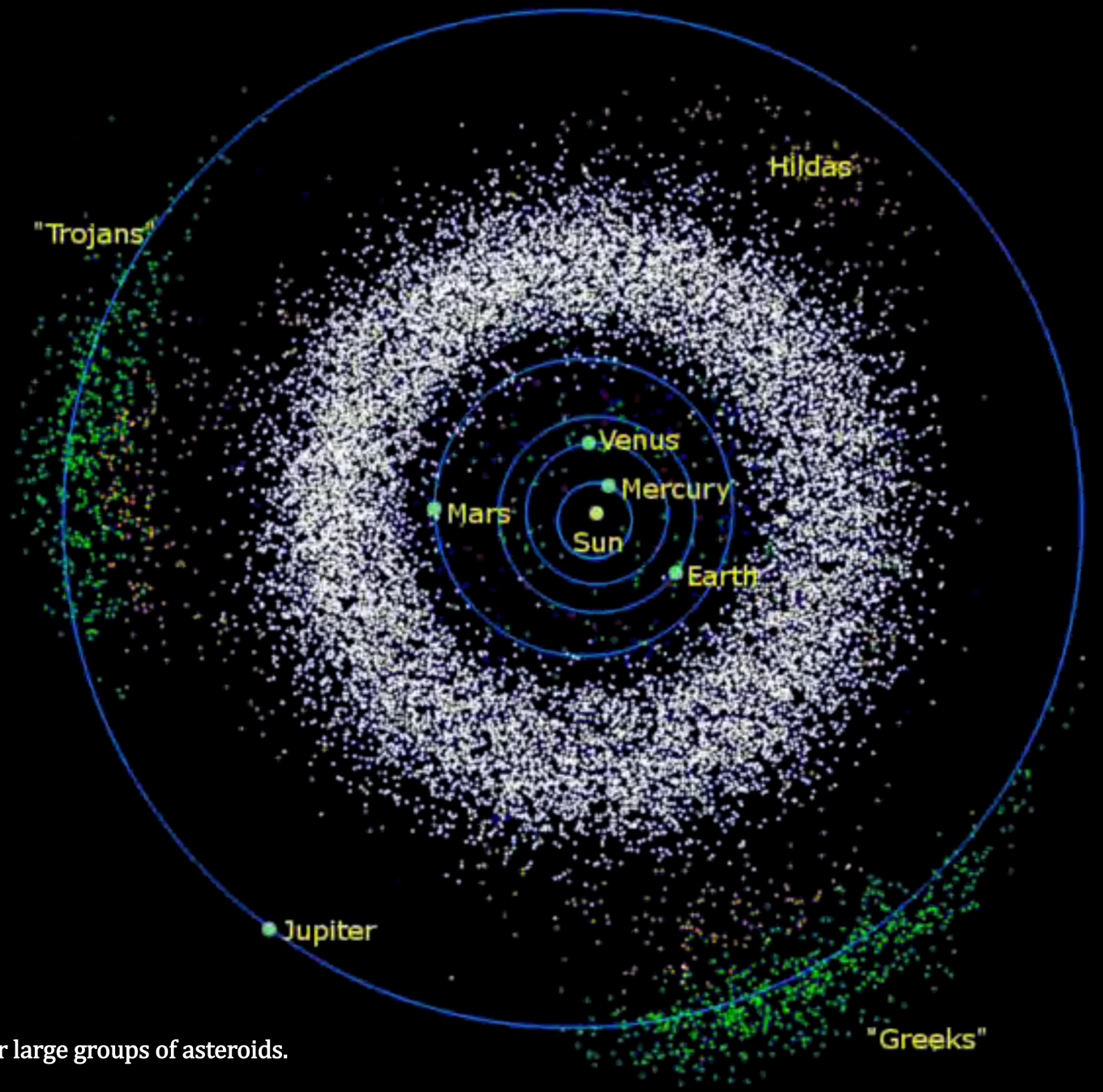


Distances In the Solar System (Logarithmic)
Credits: NASA / JPL-Caltech

Pluto and other Trans-Neptunian Objects (TNOs). Most of them are also considered dwarf planets.
Credits: Lexicon (Wikipedia)

Small solar system bodies

- Small solar system bodies (SSSBs) were defined in 2006 as objects in the solar system that are not planets, dwarf planets, or moons.
- SSSBs include:
  - Asteroids.
  - Comets.
  - Any trans-Neptunian objects that are not dwarf planets.
  - Trojans, which share the orbit of a planet or moon; most share the orbit of Jupiter.
  - Centaurs, which have characteristics of both asteroids and comets, and exist between Jupiter and Neptune.



The asteroid belt (white) and some other large groups of asteroids.
Credits: Mdf (Wikipedia)

Comets

- Comets are small solar system bodies composed of ice, dust, and small rocks.
- The nucleus of a comet is the solid part, which can be between a few hundred meters to tens of kilometers across.
- When a comet passes close to the Sun, it warms up and begins to release gas.
- This produces a visible atmosphere (a coma) and often also a tail.
- The coma may be up to 15 times Earth's diameter, and the tail may be as long as 1 AU.

Comets

- The brightest comets may be seen from Earth with the naked eye.
- This happens roughly once per year.
- Comets have been observed and recorded since ancient times.
- They can make an arc of up to 30° (60 Moons) across the sky.

Comet C/2006 P1 McNaught in the sky in 2007.
Credits: fir0002 (Wikipedia)

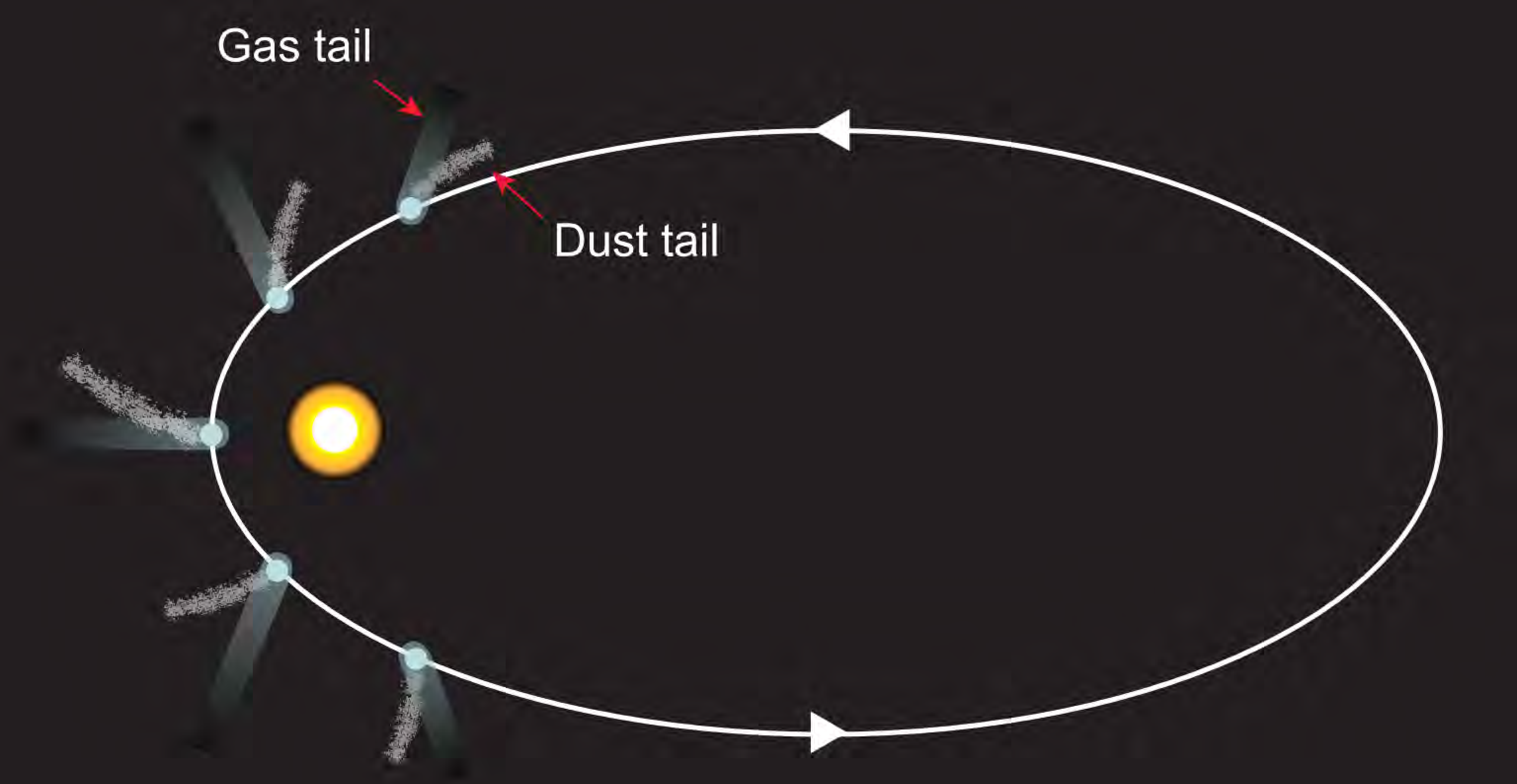
Comet C/2020 F3 NEOWISE in the sky in 2020.
Credits: Dbot3000 (Wikipedia)

Comets

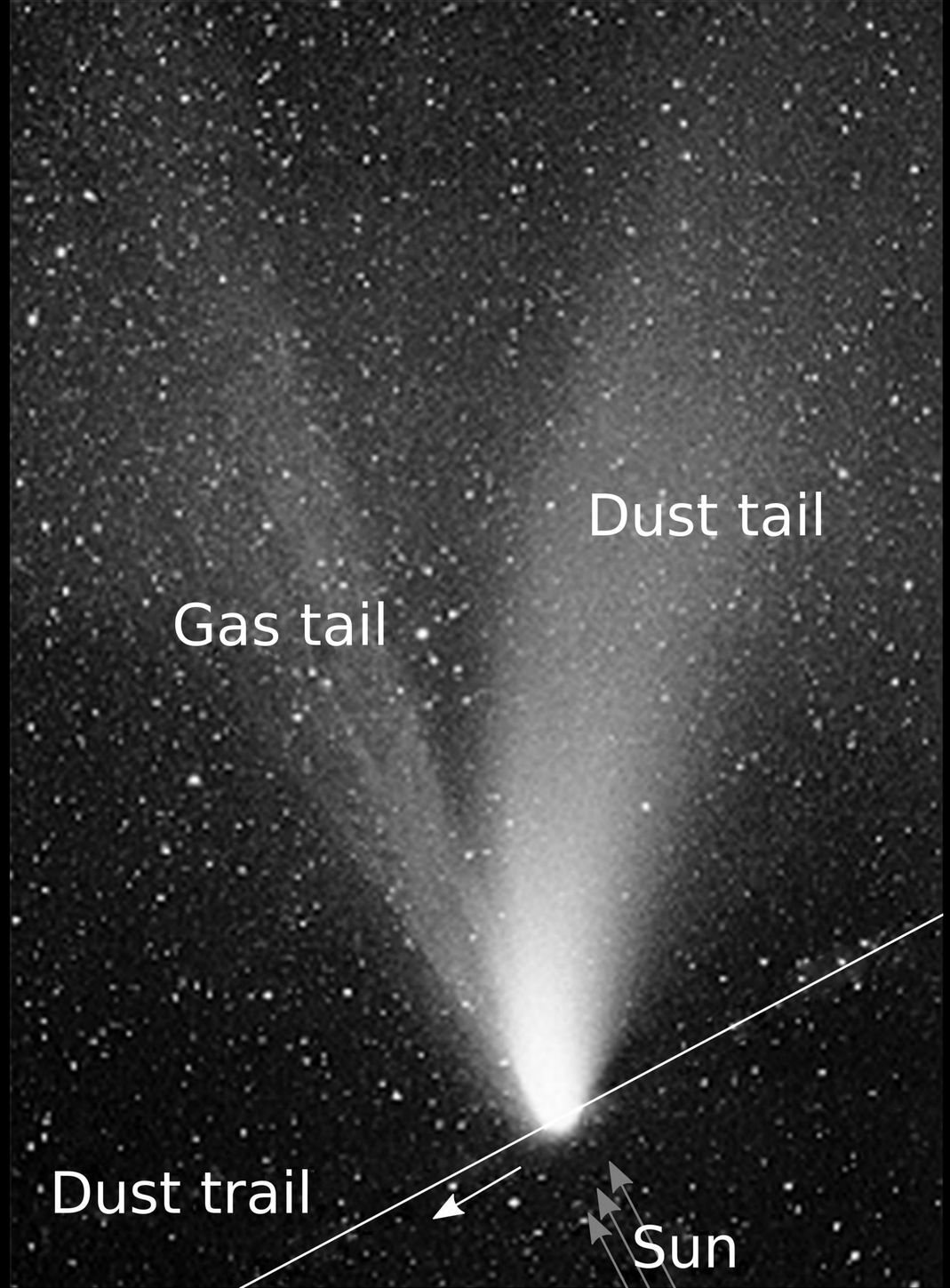
- Usually, comets have highly eccentric elliptical orbits. Their orbital periods range from several years to several millions of years.
- Short-period comets originate in the Kuiper belt. Long-period comets are thought to originate in the Oort cloud.
- There are currently more than 4,500 known comets, but their true numbers are estimated at ~1 trillion.

Comets

- Comets have two tails: a dust tail and a gas tail. Each points in a slightly different direction.
- The gas tail always points directly away from the Sun, because it is pushed away by the solar wind.
- The dust tail is made of larger particles, so it is not strongly affected by solar wind.



A typical orbit of a comet, showing its two tails.
Credits: Юкатан (Wikipedia)



Close up on the two tails (artist's concept).
Credits: Юкатан (Wikipedia)

Conclusions

- In this lecture, we learned about many different objects in our solar system.
- Who knows, maybe one day you will even be able to visit some of them in person!

- Reading: OpenStax Astronomy, chapters 8-14.
- Exercises: Practice questions will be posted on Teams.

What’s next?

- To continue learning about astronomy, take ASTR 1P02:
  - Every winter term: online and in person.
  - Every spring term: online only, heavily accelerated (1 month instead of 3).
- In ASTR 1P02 we will learn more advanced material, including:
  - Stars and galaxies.
  - Black holes, curved spacetime, and general relativity.
  - Dark matter and dark energy.
  - Cosmology and the Big Bang.
  - Life beyond Earth.
- I hope to see you all there! Good luck in the final exam, and have a nice break! ☺