ASTR 1P01

Brock University

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Lecture 8: The solar system

We will learn about…

- The planets in the solar system.
- Other objects, such as moons, comets, asteroids, and dwarf planets.
- Past and future human exploration of the solar system.
- How the solar system was created.

Hubble Space Telescope Image of Jupiter
Credits: NASA, ESA, STScI, A. Simon (Goddard Space Flight Center), and M.H. Wong (University of California, Berkeley) and the OPAL team

Solar system objects

- The solar system is the planetary system containing the Sun and the 8 planets orbiting it, including Earth, as well as many smaller objects.
- Most other stars have planetary systems too. The term “solar system” refers only to the one around our Sun, a.k.a. Sol.
- Other planetary systems are sometimes referred to as exoplanetary systems.

Solar system objects

- The 4 planets closest to the Sun are called the inner planets or terrestrial planets: Mercury, Venus, Earth, and Mars.
- The inner planets are relatively small.
- They are composed primarily of rock and metal.
- They have solid surfaces with craters, mountains, and volcanoes.

Solar system objects

- The 4 planets farther from the Sun are called the jovian planets or giant planets: Jupiter, Saturn, Uranus, and Neptune.
- The giant planets are much larger than the inner planets (1,300 Earths can fit into Jupiter).
- They are composed primarily of lighter ices, liquids, and gases.
- They do not have solid surfaces – they are basically giant oceans.

Solar System in true imagery, color and size

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

Distances in the Solar System (distances to scale, sizes not to scale)
Credits: CactiStaccingCrane (Wikipedia)

Orbits of the Planets and Dwarf Planets
Credits: OpenStax Astronomy

Mass distribution of the solar system

Object	Percentage of Total Mass
Sun	99.80
Jupiter	0.10
Comets	0.0005–0.03 (estimate)
Other planets and dwarf planets	0.04
Moons and rings	0.00005
Asteroids	0.000002 (estimate)
Cosmic dust	0.0000001 (estimate)

Properties of the planets

Name	Distance from Sun (AU)	Revolution Period (yr)	Diameter (km)	Mass (10^{23} kg)	Density (kg/m^3)
Mercury	0.39	0.24	4,878	3.3	5,400
Venus	0.72	0.62	12,120	48.7	5,200
Earth	1.00	1.00	12,756	59.8	5,500
Mars	1.52	1.88	6,787	6.4	3,900
Jupiter	5.20	11.86	142,984	18,991	1,300
Saturn	9.54	29.46	120,536	5686	700
Uranus	19.18	84.07	51,118	866	1,300
Neptune	30.06	164.82	49,660	1030	1,600

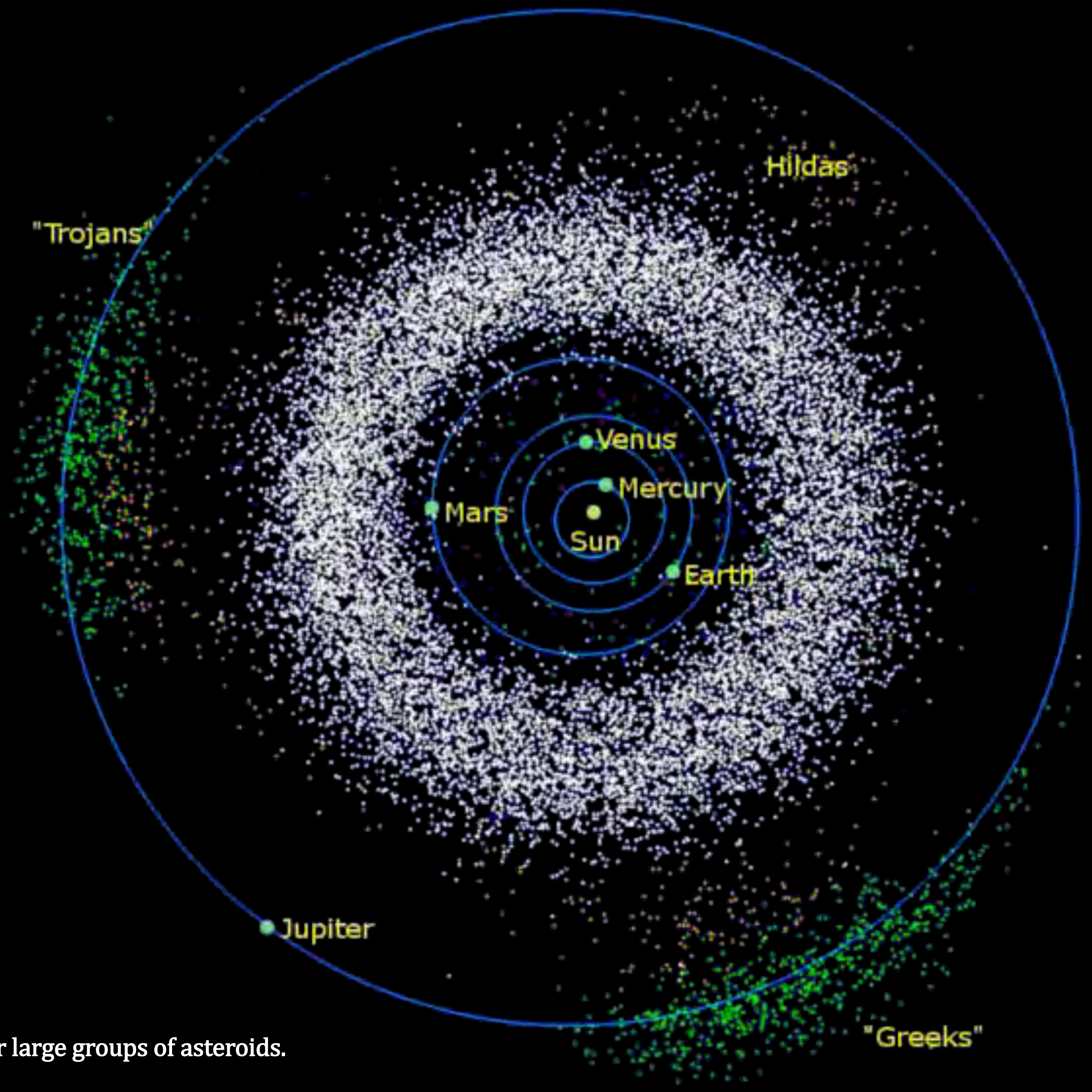
Solar system objects

- All planets except Mercury and Venus have moons.
- There are at least 210 moons in the solar system, orbiting planets and dwarf planets.
- Some moons are as big as small planets!
- The giant planets also have rings made up of countless small bodies, which range in size from grains of dust to mountains.
- Saturn’s rings are the most famous, and easiest to see.

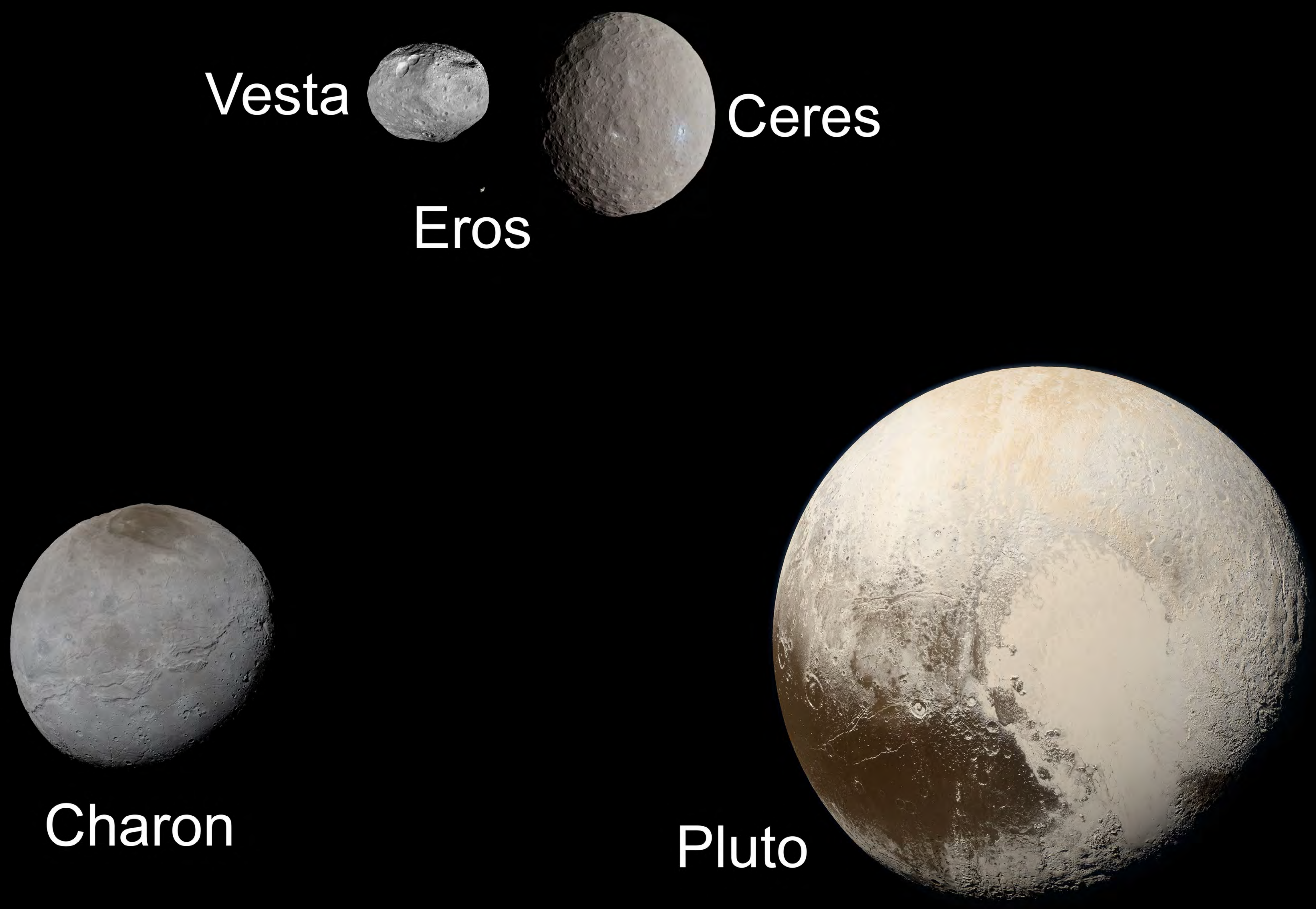
Natural color image of Saturn and 6 of its moons, taken by Cassini in July 2008.
Credits: NASA / JPL / Space Science Institute

Solar system objects

- Asteroids are smaller rocky bodies that orbit the Sun. Most are in the asteroid belt, between the orbits of Mars and Jupiter.
- Many are remnants of the initial matter of the solar system, before the planets formed.
- Some of the smallest moons of the planets are most likely captured asteroids.
- ~60% of the mass of the asteroid belt is contained in the 4 largest asteroids: Ceres, Vesta, Pallas, and Hygiea.
- Ceres is the largest asteroid, large enough to be a dwarf planet.



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



The asteroids Ceres, Vesta, and Eros compared to the sizes of Pluto and its moon Charon.
Credits: Justin Cowart, NASA/JPL, NASA/JPL-Caltech/UCAL/MPS/DLR/IDA, NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Alex Parker

Solar system objects

- Comets are small icy bodies composed mostly of frozen water (H_2O), carbon dioxide (CO_2), and carbon monoxide (CO).
- They orbit the Sun at much larger distances, where the temperature is cold.
- When they get closer to the Sun, they warm up and begin to release gases.
- This produces a visible atmosphere (the coma) and sometimes a tail.

Comet ISON
Credits: Damian Peach / SkyandTelescope.com

Solar system objects

- The solar system also contains countless grains of broken rock called cosmic dust.
- Millions of these particles enter Earth’s atmosphere every day.
- When they do, they burn up and produce a flash of light called a meteor. (The meteor is the flash of light, not the particle itself.)
- If a particle is large enough to survive this and land on Earth, it’s known as a meteorite.

A meteor during the peak of the 2009 Leonid Meteor Shower
Credits: Navicore (Wikipedia)

View of a meteor from the International Space Station
Credits: Navicore (Wikipedia)

The 60 ton, 2.7 m long Hoba meteorite in Namibia – the largest known intact meteorite.
Credits: Calips (Wikipedia)

Simulation

- I will show you a real-time simulation of the solar system using Universe Sandbox:

  https://universesandbox.com/

- This software costs money, but it’s worth it! It also has a VR mode.

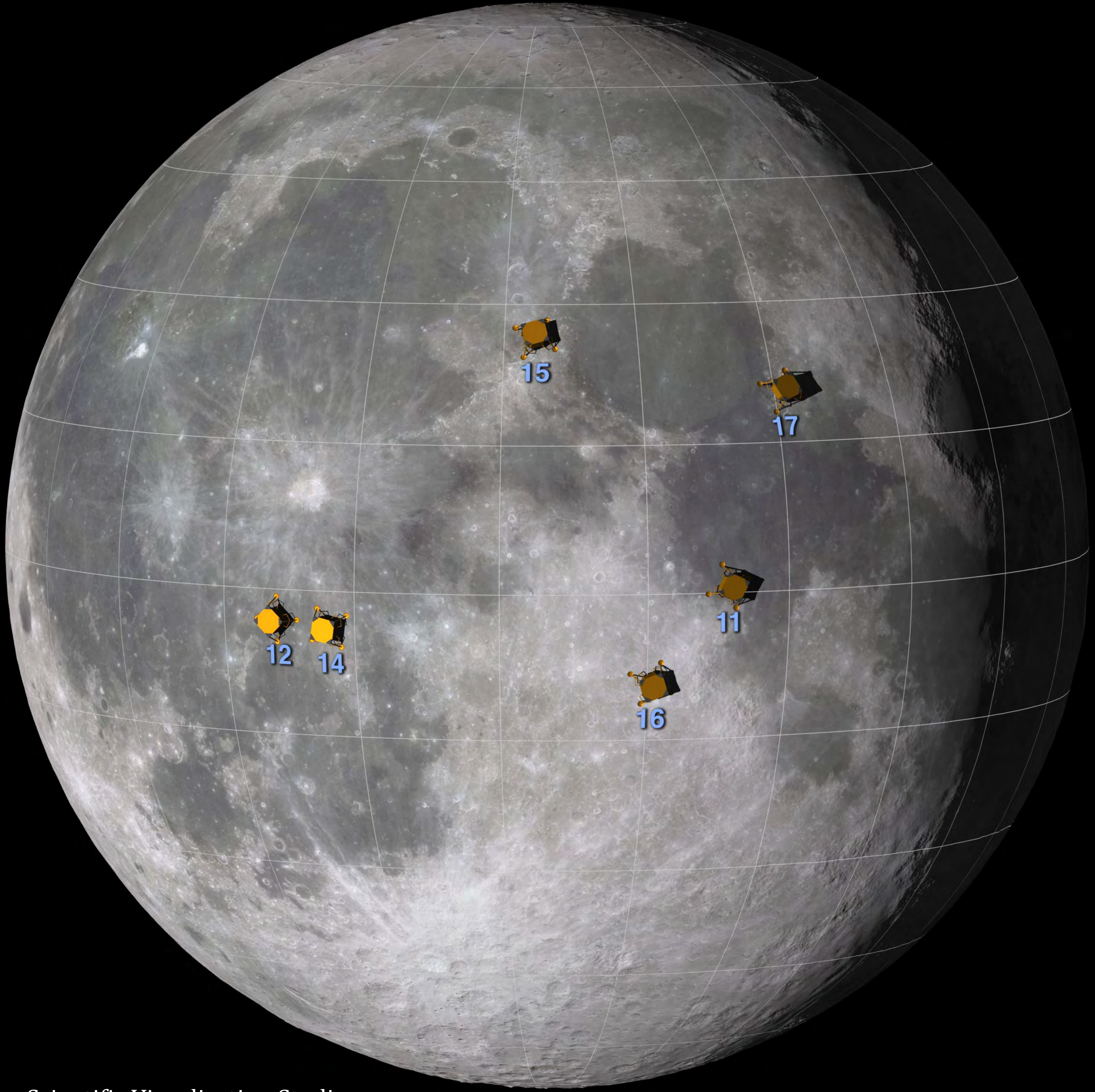
Solar system exploration

- Our solar system is the only place in the universe we have explored directly.
- Humans have visited the Earth's Moon in person, and plan to visit other places, such as Mars.
- In the coming centuries, we could permanently colonize the Moon and Mars, as well as other planets or moons.
- We have also explored many objects in the solar system indirectly through spacecraft and probes.

Exploration: The Moon

- Numerous uncrewed missions since 1958: Luna, Ranger, Surveyor, Lunar Orbiter, Zond, and many more.
- 6 crewed Moon landings between 1969 and 1972: Apollo 11, 12, 14, 15, 16, 17.
- Ongoing mission: Artemis (NASA, CSA, ESA, JAXA).
  - Artemis I: uncrewed, launched, November 16, 2022.
  - Artemis II: 4-person lunar flyby, planned for 2024.
  - Artemis III: 4-person lunar orbit with 2-person lunar landing, planned for 2025.
  - Long-term goal: establish a permanent base camp on the Moon.

Apollo 15 Astronauts on the Moon
Credits: David R. Scott, NASA



Map of Apollo landings on the Moon
Credits: NASA / Goddard Space Flight Center Scientific Visualization Studio

Artemis I launch, NASA’s Kennedy Space Center in Florida, November 16, 2022 at 01:47 EST
Credits: NASA/Joel Kowsky

Video

- I will show a video from NASA summarizing the launch of Artemis I to the Moon.
- The video can be found at this URL:

https://youtu.be/mYTvg2abusc

- Want to see more? Check out the complete live broadcast:

https://youtu.be/CMLD0Lp0JBg

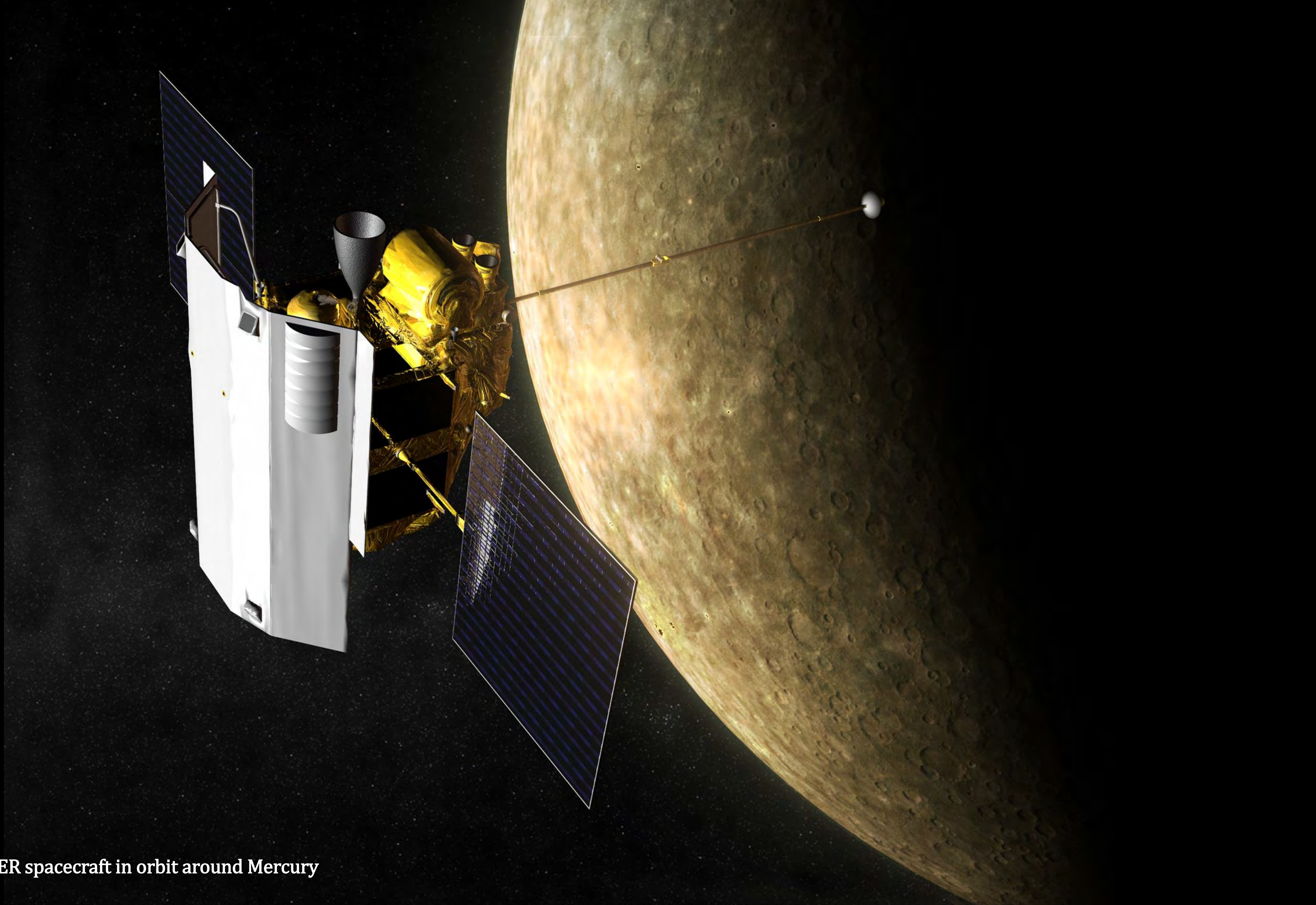
Exploration: Mercury

- Mercury is the least explored inner planet.
- Since it's very close to the Sun it is also moving very fast.
  - It has to travel fast to stay in orbit, otherwise it would fall into the Sun!
- This means a spacecraft must accelerate up to ~48 km/s to catch up with Mercury and stay in orbit around it.
- Also, spacecraft near Mercury are strongly influenced by the Sun's gravity, and need to use a lot of fuel to resist it.
- Since the atmosphere of Mercury is very thin, it cannot be used to slow down the spacecraft, as with other planets.

Exploration: Mercury

- Mariner 10 was the first to observe Mercury, in 1974.
  - It was placed in orbit around the Sun, not Mercury, since that's easier.
  - It encountered Mercury two more times, in 1974 and 1975.
- MESSENGER ("Mercury Surface, Space Environment, Geochemistry, and Ranging") was the first to orbit Mercury, in 2011.
  - It needed to travel ~8 billion km over ~6.5 years to maneuver into orbit.
  - It continued collecting data until 2015, and then crashed (intentionally) onto the surface.
- BepiColombo was launched in 2018 and is scheduled to arrive at Mercury in 2025.

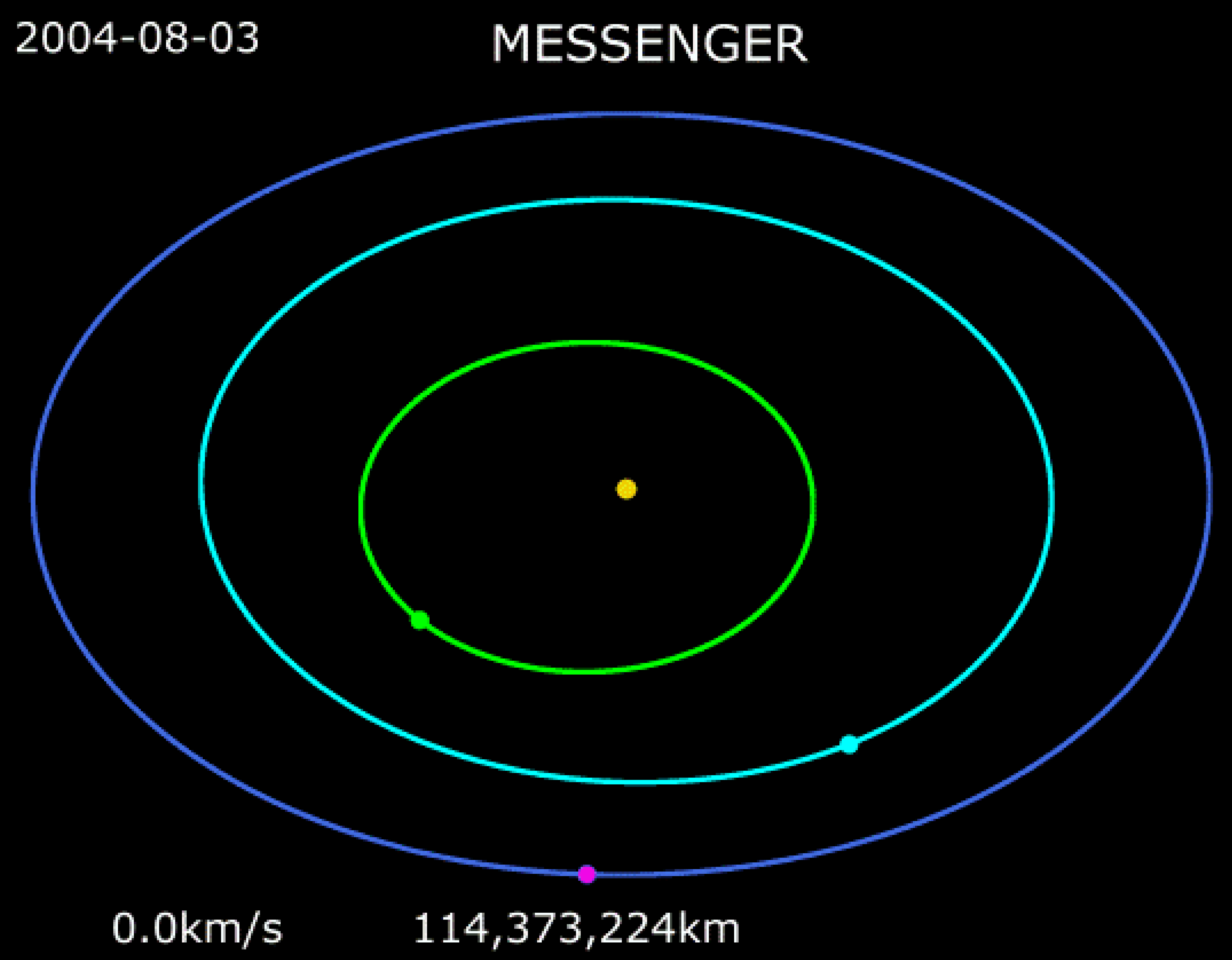
Photograph of Mercury from MESSENGER's first flyby of the planet
Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington



Artist's depiction of the MESSENGER spacecraft in orbit around Mercury
Credits: NASA / JHU/APL

Exploration: Mercury

- This is MESSENGER's trajectory from launch in 2004 until mission end in 2015.
- Legend:
  - Pink: MESSENGER
  - Blue: Earth
  - Aqua: Venus
  - Green: Mercury
- Animation URL: https://en.wikipedia.org/wiki/File:Animation_of_MESSENGER_trajectory.gif



Exploration: Venus

- The Venera program sent many probes to Venus between 1966 and 1984.
- The Pioneer Venus project sent a multiprobe into the atmosphere in 1978 and operated an orbiter between 1978 and 1992.
- Vega 1 and 2 visited Venus in 1985.
- Magellan mapped the surface between 1990 and 1994.

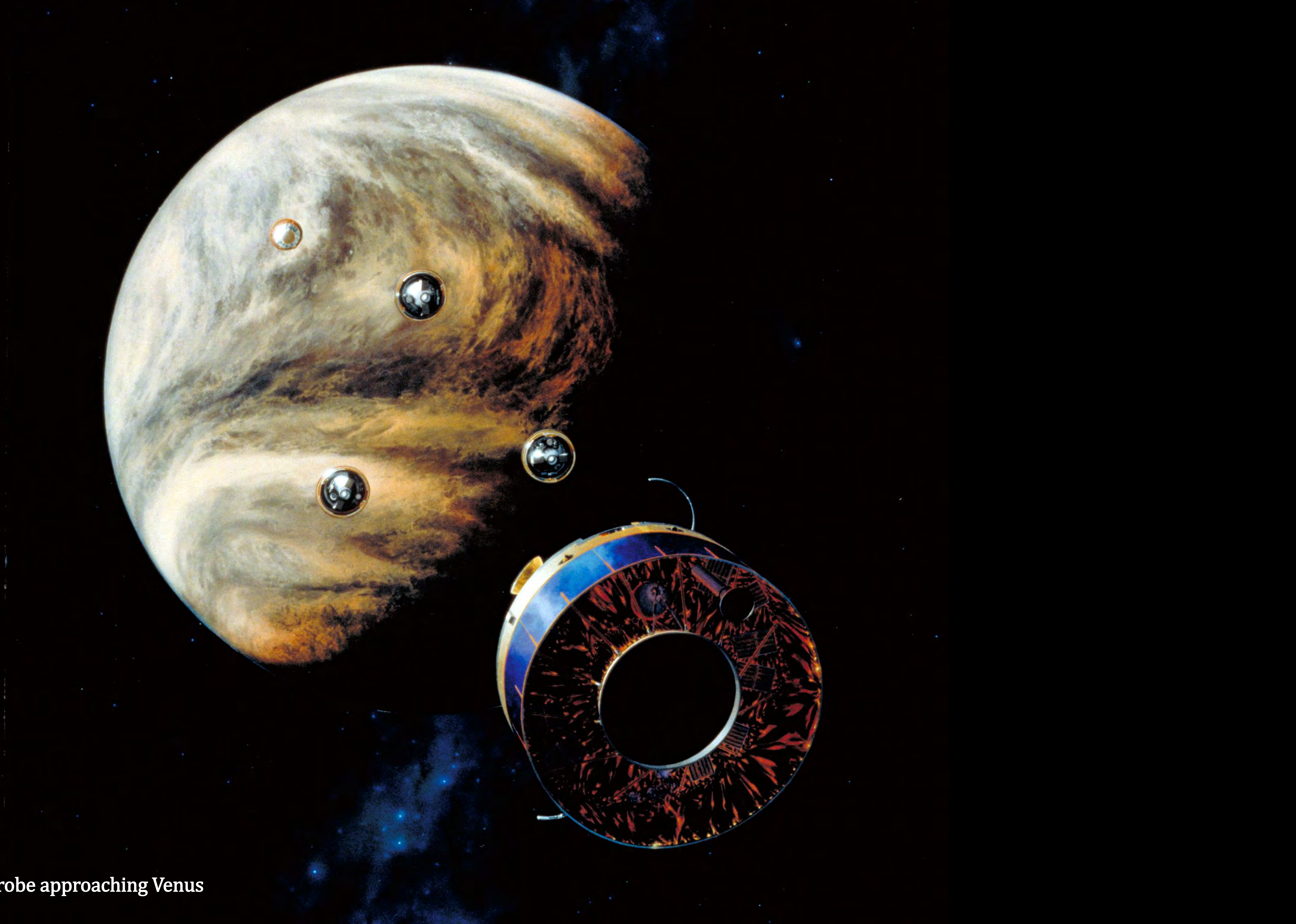


Illustration of the Pioneer Venus Multiprobe approaching Venus
Credits: NASA/ Paul Hudson

3D view of the surface of Venus from the Magellan probe (reprojected from stereo imaging)
Credits: NASA/JPL

Exploration: Mars

Mars has been explored by many spacecraft, including:

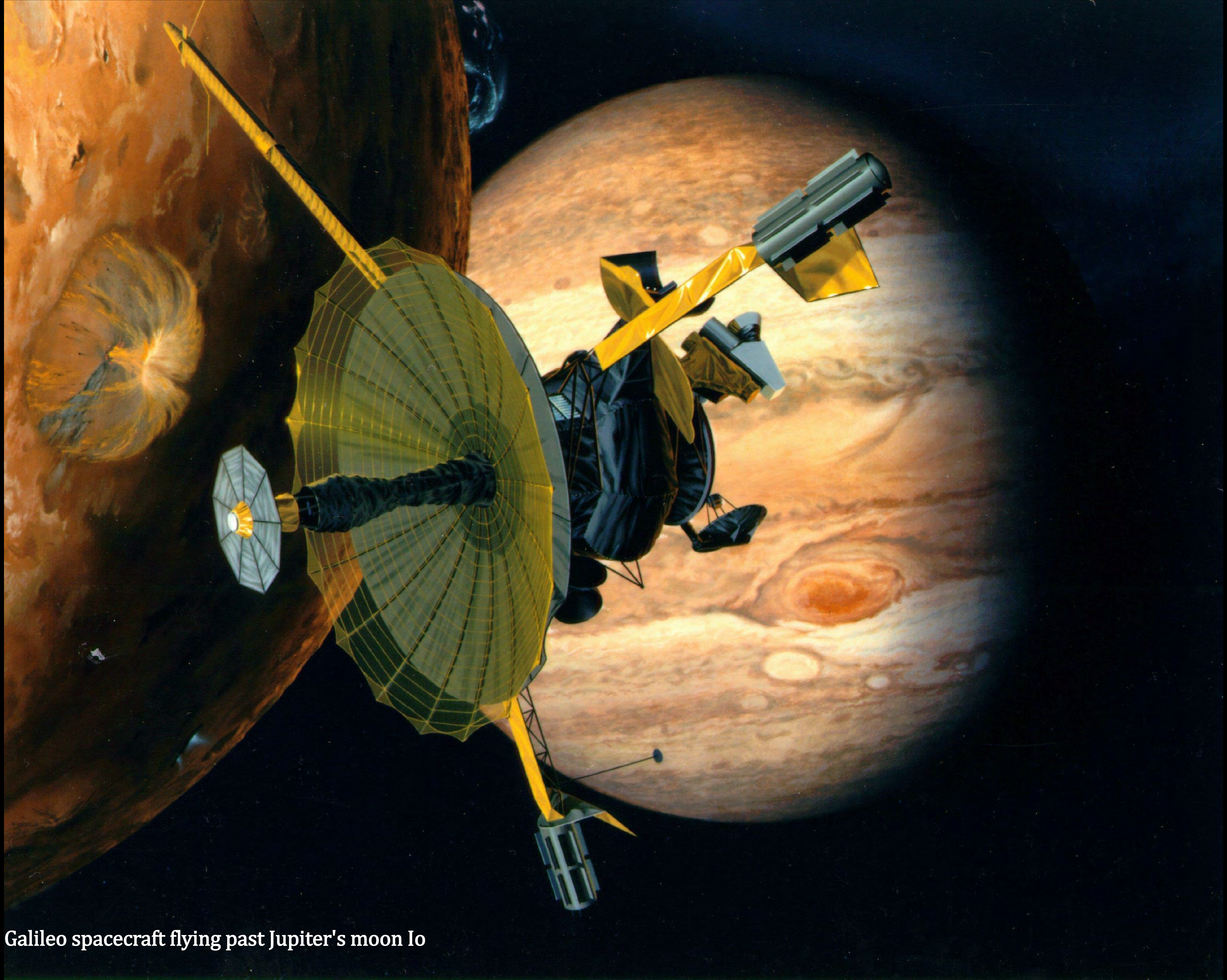
- The Mars probes, 1960s-1970s
- Viking 1 & 2, 1976
- Pathfinder, 1997
- Mars Polar Lander, 1999
- Beagle 2, 2003
- Spirit & Opportunity, 2004
- Phoenix, 2008
- Curiosity, 2012
- InSight, 2018
- Perseverance rover & Ingenuity helicopter, 2021
- Tianwen-1 lander & Zhurong rover, 2021

“Selfie” from NASA’s Mars Perseverance rover
Credits: NASA/JPL-Caltech, video URL: https://en.wikipedia.org/wiki/File:Perseverance-Selfie-at-Rochette-Horizontal-V2.gif

The Ingenuity Mars Helicopter flying in 2021. Video footage from NASA's Mars Perseverance rover.
Credits: NASA/JPL-Caltech/ASU/MSSS, video URL: https://en.wikipedia.org/wiki/File:Flight_13_zoomed-in_animation_from_Perseverance_Mastcam.gif

Exploration: Jupiter

- Galileo orbited Jupiter from 1995 to 2003.
- Juno has been orbiting it since 2016.
- Jupiter Icy Moons Explorer is expected to launch in 2023 and arrive in 2031.
- Jupiter was also studied and photographed by other spacecraft that flew by it on their way to other planets.



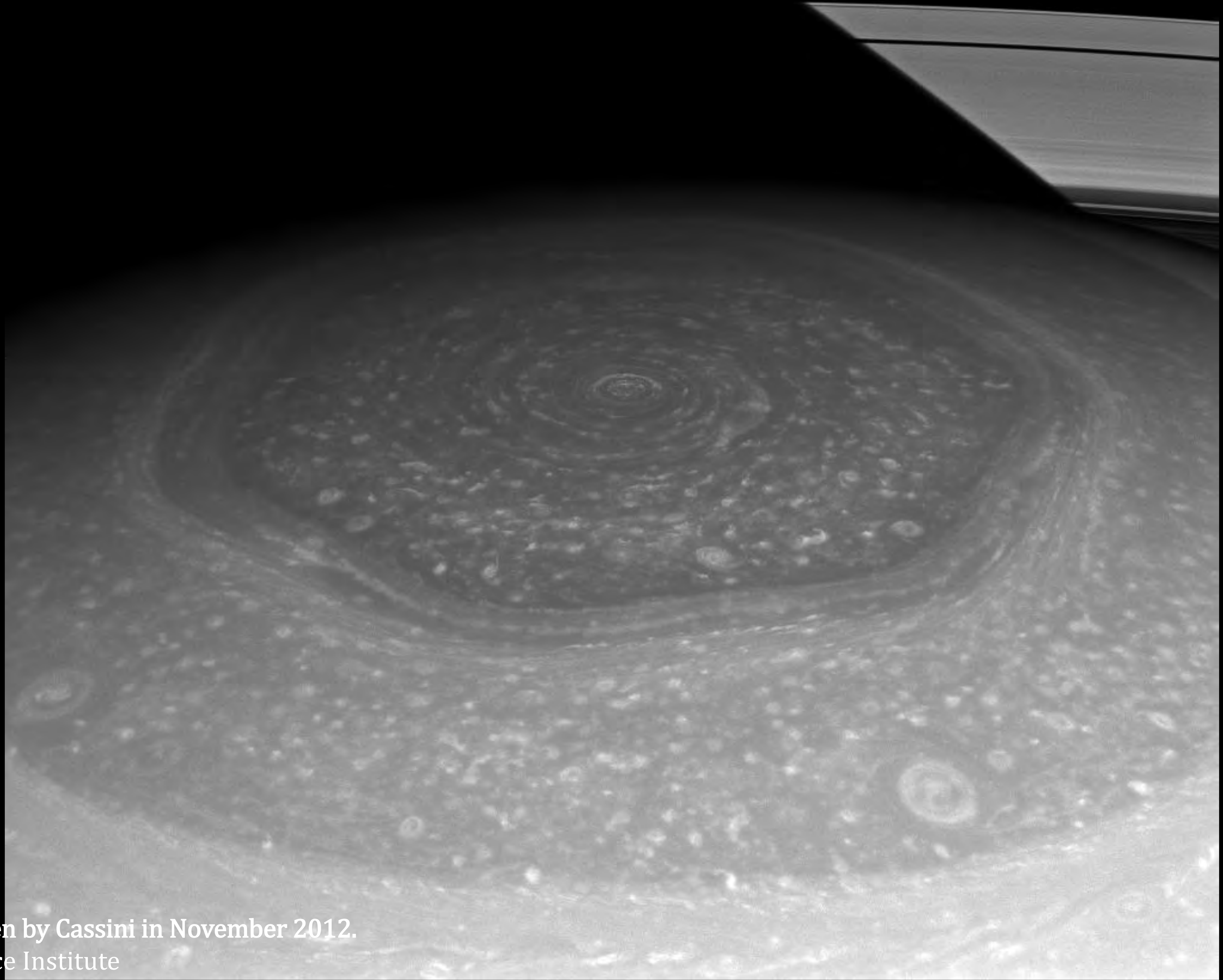
Artist's rendering of NASA's Galileo spacecraft flying past Jupiter's moon Io
Credits: NASA

Close-up of Jupiter’s moon Ganymede, taken by Juno in 2021.
Credits: NASA/JPL-Caltech/SwRI/MSSS

Exploration: Saturn

- The Cassini–Huygens spacecraft was launched in 1997.
- It entered orbit around Saturn in 2004 and stayed there until 2017.
- The Huygens probe was released in 2004 and landed on Saturn's moon Titan in 2005. It sent data to Earth for ~90 minutes.
- This was the first landing in the outer solar system and the first ever landing on a moon other than Earth's Moon.

Natural color image of Saturn and 6 of its moons, taken by Cassini in July 2008.
Credits: NASA / JPL / Space Science Institute



Saturn's north polar hexagon. Image taken by Cassini in November 2012.
Credits: NASA/JPL-Caltech/Space Science Institute

Video

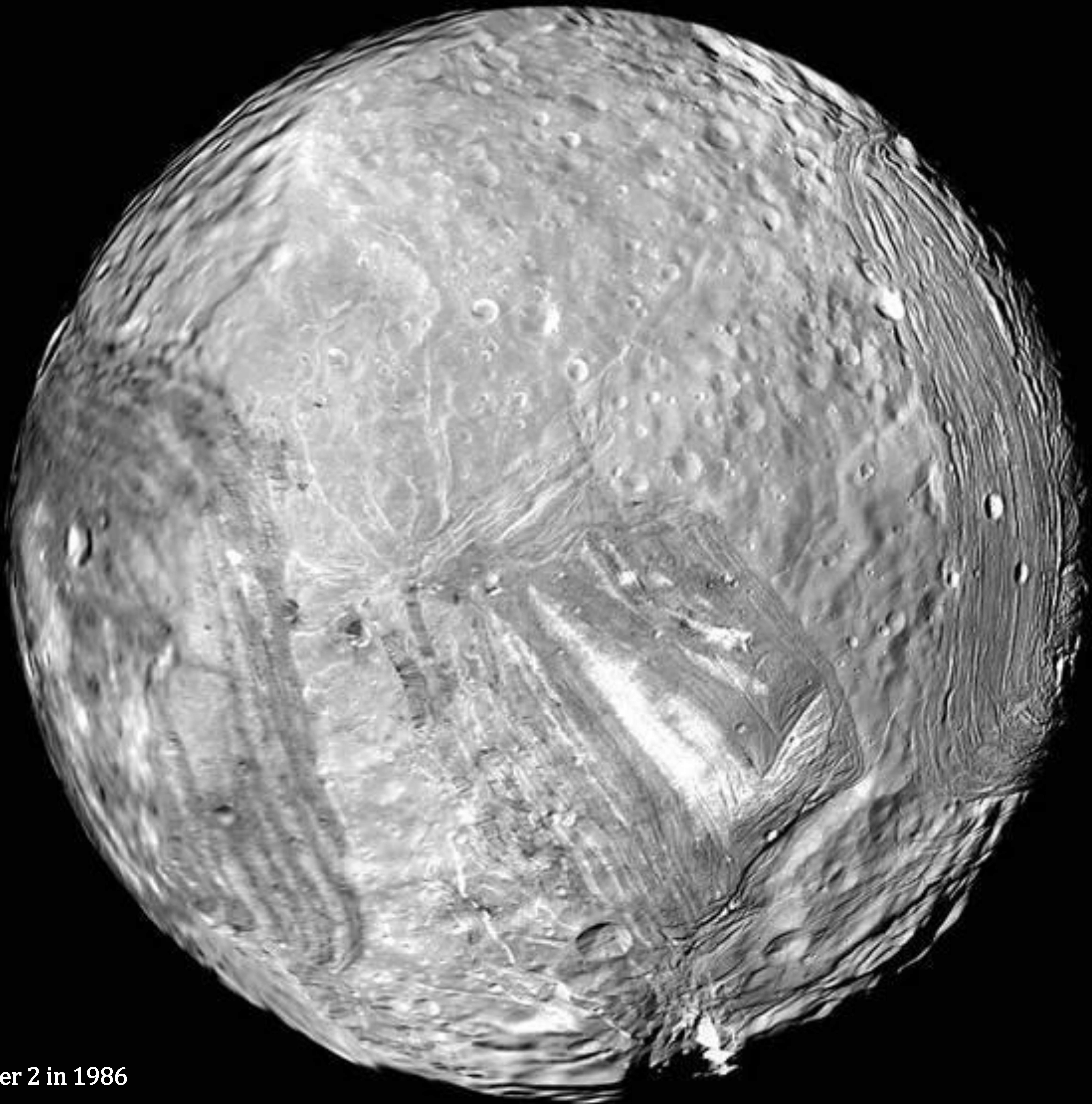
- This video described Cassini's "Grand Finale" at the end of its mission, in 2017.
- It can be found at this URL:

https://youtu.be/xrGAQCq9BMU

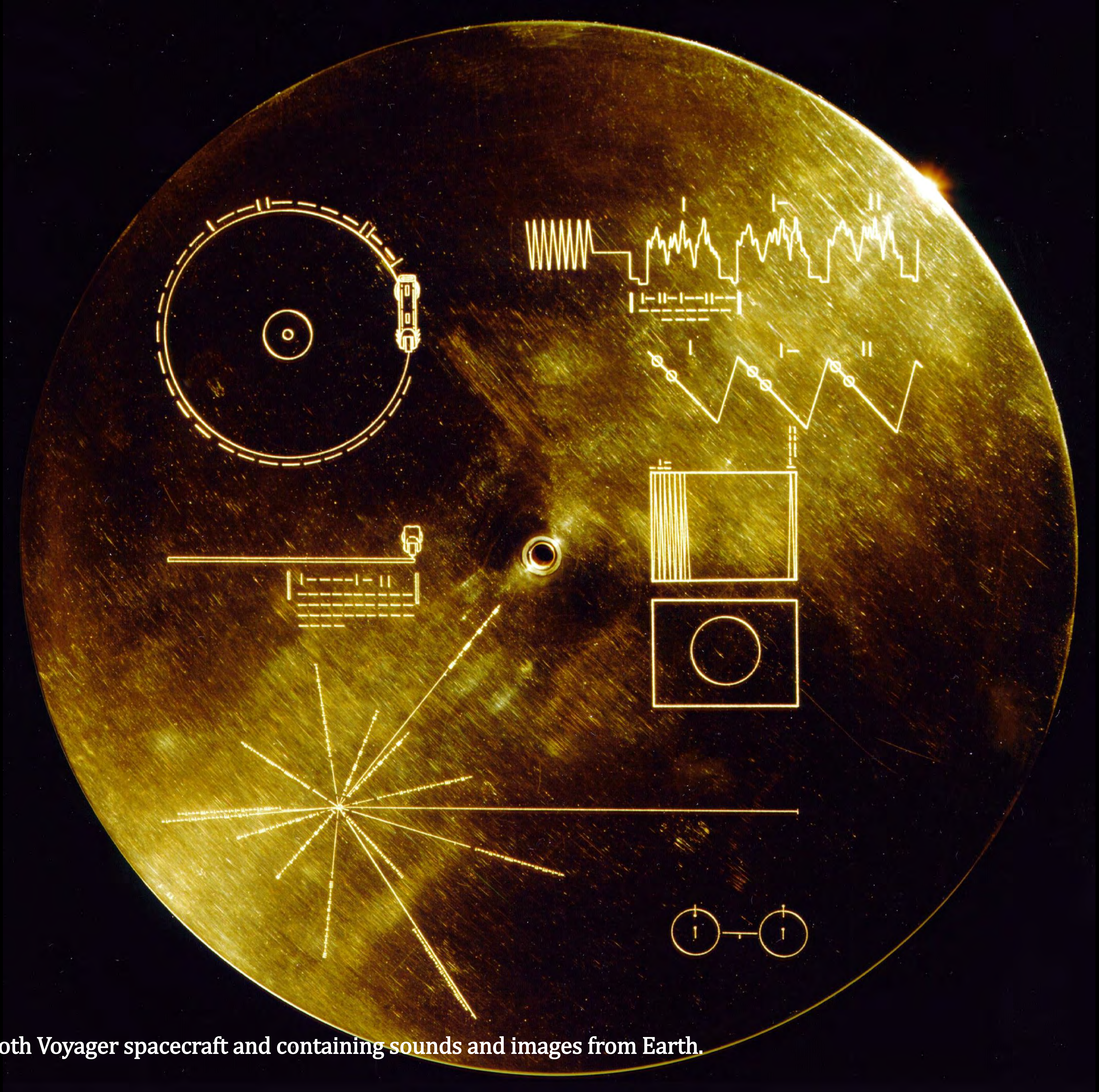
Exploration: Uranus

- So far, Uranus has only been explored by NASA's Voyager 2 spacecraft.
- It made its closest approach to Uranus on January 24, 1986.
- Voyager 2 discovered 10 moons, studied the planet's atmosphere, and examined its ring system.

A true-color image of Uranus taken by Voyager 2 in 1986
Credits: NASA


Uranus' icy moon Miranda as seen by Voyager 2 in 1986
Credits: NASA/JPL-Caltech

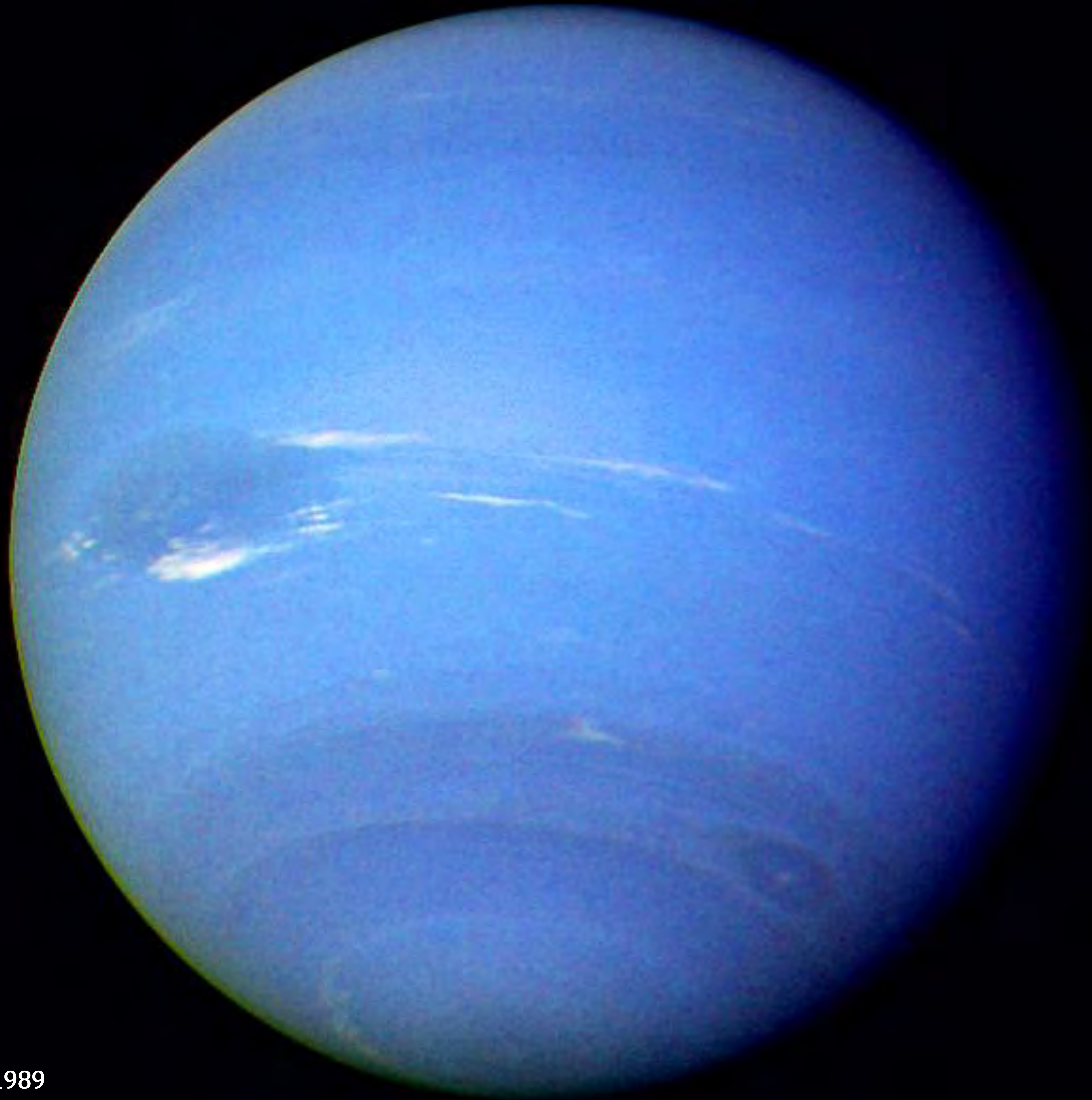
The Voyager spacecraft. Note the golden record attached to it.
Credits: NASA/JPL-Caltech



The Voyager golden record, attached to both Voyager spacecraft and containing sounds and images from Earth.
Credits: NASA/JPL

Exploration: Neptune

- Like Uranus, Neptune has so far only been explored by Voyager 2.
- It collected data on Neptune between August and October 1989.



Neptune as seen from Voyager 2 in August 1989
Credits: NASA/JPL

Neptune’s moon Triton as seen from Voyager 2 in August 1989
Credits: NASA/JPL

Exploration: Asteroids

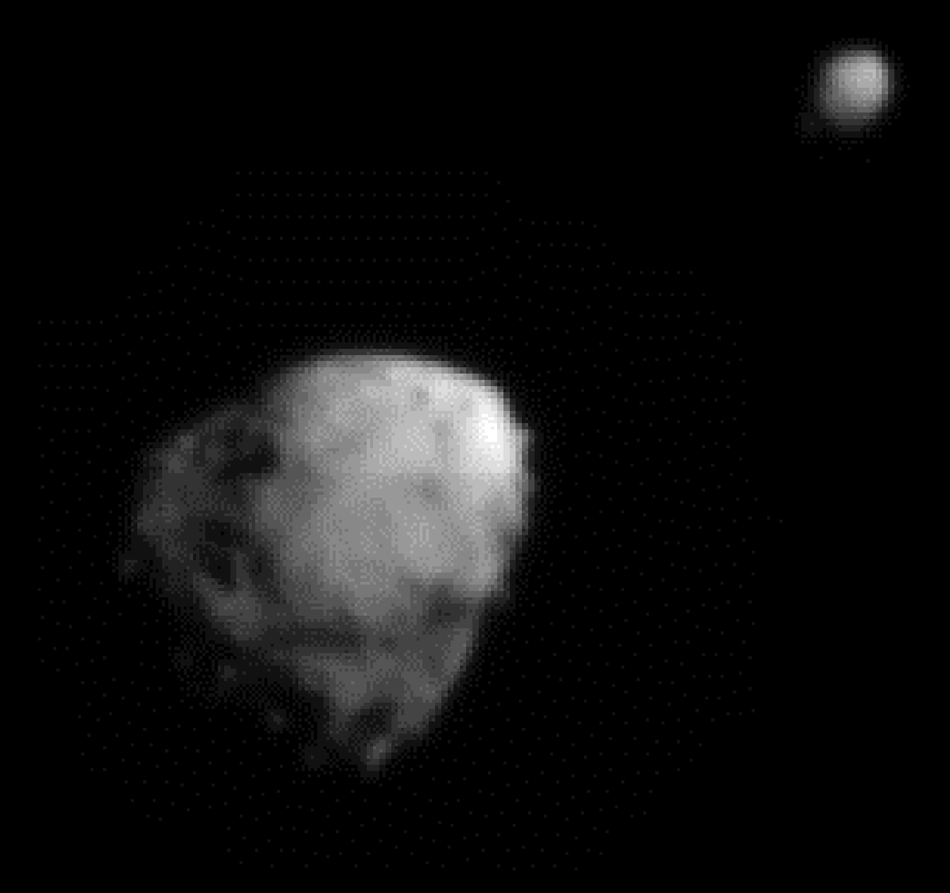
- NEAR (Near Earth Asteroid Rendezvous) Shoemaker orbited the asteroid Eros in 2000 and landed on it in 2001.
- Hayabusa explored Itokawa in 2005.
- Hayabusa2 surveyed Ryugu in 2018 and returned samples to Earth.
  - It is planned to study another asteroid, 1998 KY_{26}, in 2031.
- OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) collected a sample from Bennu in 2020 and is expected to return it to Earth in 2023.

Eros as seen from NEAR Shoemaker in 2000
Credits: NASA/JPL/JHUAPL

OSIRIS-REx collects samples from asteroid Bennu in a "Touch-And-Go" (TAG) event
Credits: NASA/Goddard/University of Arizona, video URL: https://svs.gsfc.nasa.gov/13744

Exploration: Asteroids

- DART (Double Asteroid Redirection Test) was intentionally crashed into Dimorphos, a moon (or moonlet) of the asteroid Didymos.
- Dimorphos has an average diameter of ~160 m.
- This was a test of a potential planetary defense system, in case an asteroid threatens Earth.
- However, this asteroid was NOT actually a danger to Earth, it was only a test.
- DART was successfully able to reduce the orbital speed of Dimorphos and therefore reduce its orbital radius around Didymos.

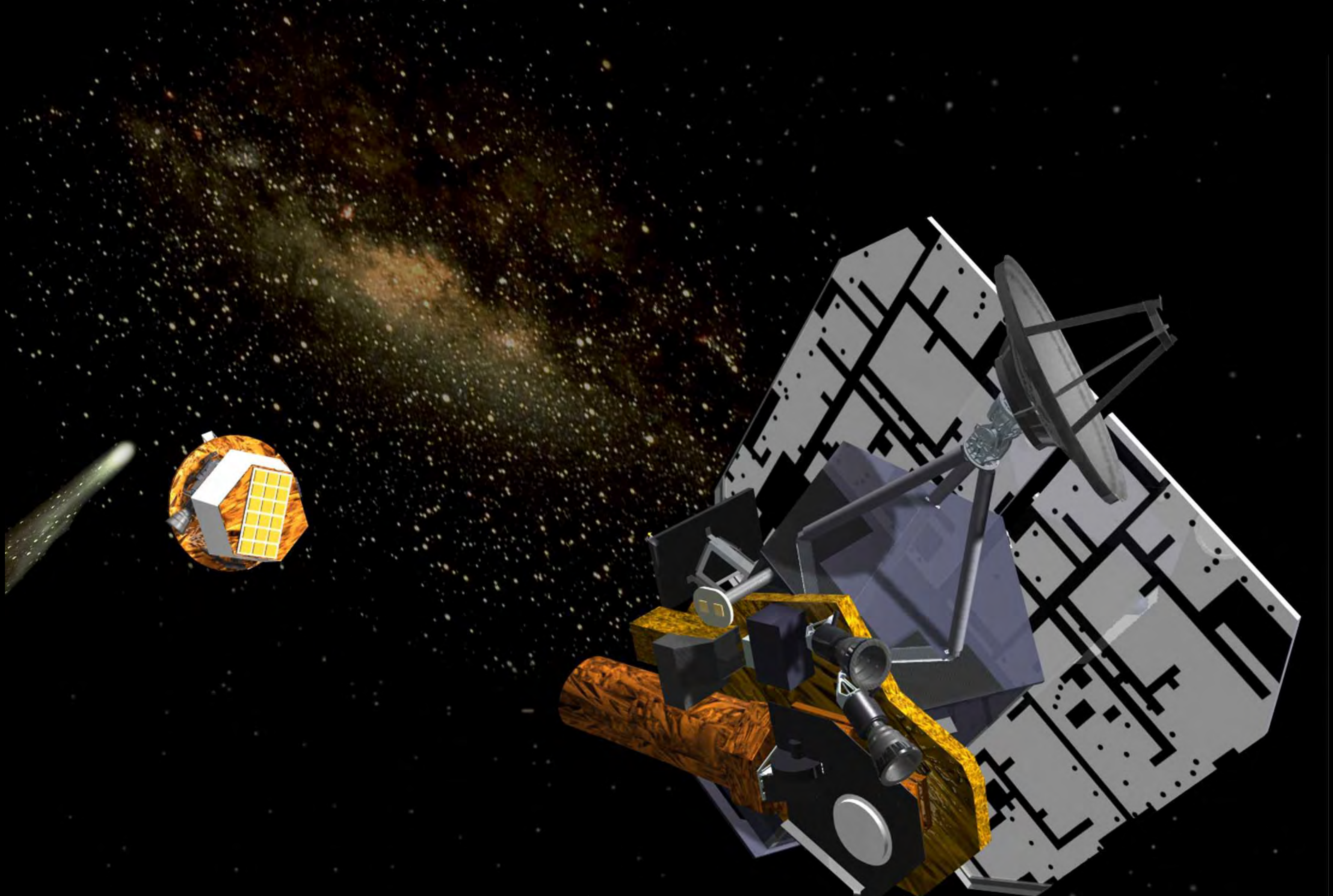


The final 5.5 minutes leading up to DART's collision with Dimorphos on September 26, 2022. Played at 10x speed, except for the last 6 images.
Credits: NASA/Johns Hopkins APL, video URL: https://dart.jhuapl.edu/Gallery/media/videos/dart_impact_replay.mp4

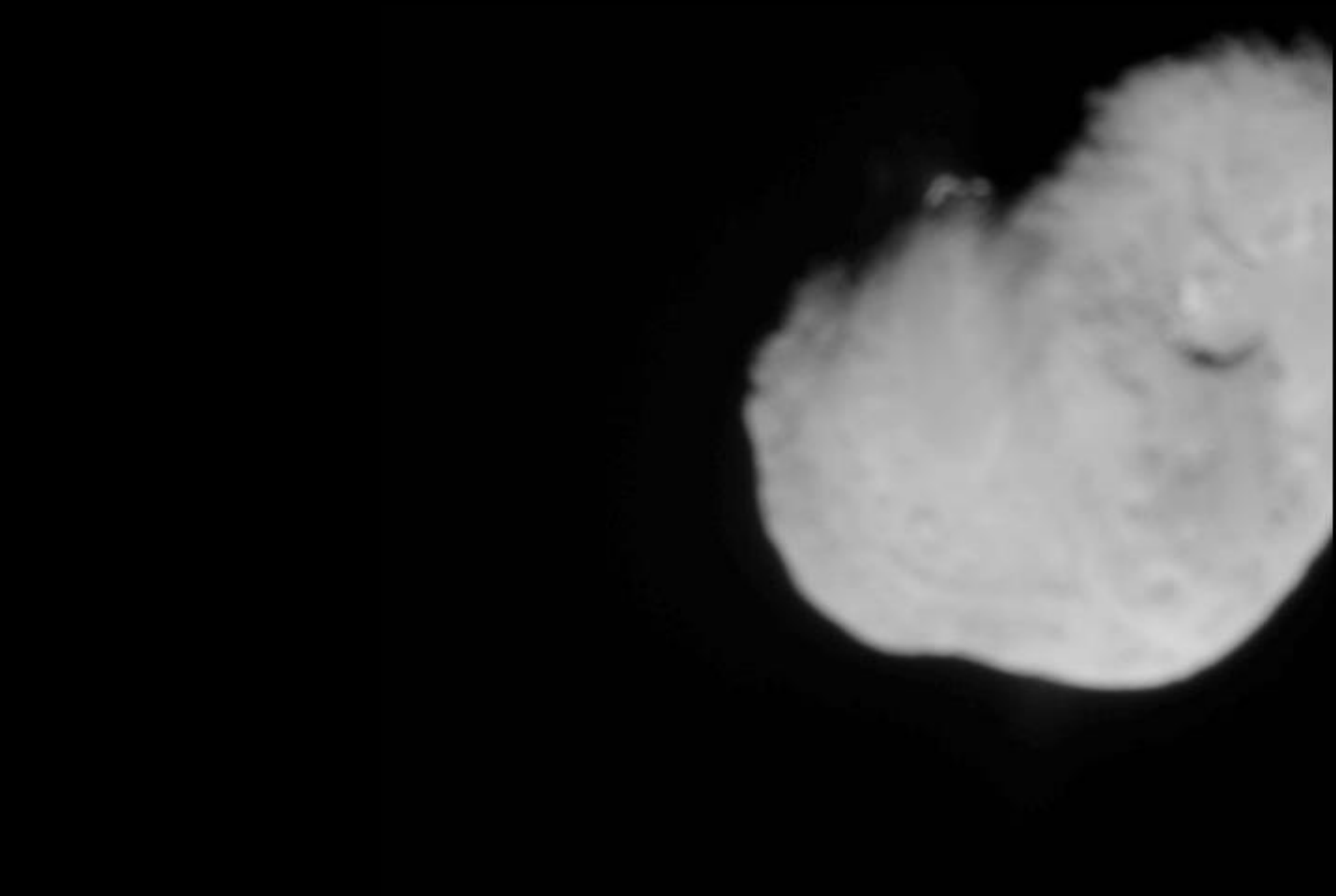
Illustration of the effect of DART's impact on the orbit of Dimorphos
Credits: NASA/Johns Hopkins APL

Exploration: Comets

- The first close encounter with a comet (at 596 km) was by Giotto, which flew by Halley's Comet in 1986.
- Stardust was the first to collect samples from a comet, Wild 2 (pronounced “vilt”), in 2004. It returned them to Earth in 2006.
- Deep Impact studied the composition of the comet Tempel 1 by deliberately crashing a spacecraft into its surface to eject material.
- Rosetta performed a detailed study of comet Churyumov–Gerasimenko in 2014.
  - Its lander, Philae, was the first to land (non-destructively) on a comet’s nucleus.



Artist's impression of the Deep Impact space probe after deployment of the Impactor (the part that crashed into the comet)
Credits: NASA/JPL



Video from Deep Impact showing the impact with the comet on July 3, 2005. The Impactor placed itself in front of the comet for impact.
Credits: NASA/JPL, video URL: https://en.wikipedia.org/wiki/File:HRIV_Impact.gif

Comet 67P/Churyumov-Gerasimenko as seen from Rosetta at a distance of 162 km on April 15, 2015. The comet is ~4.1 km long.
Credits: ESA, Rosetta, NAVCAM; processing by Giuseppe Conzo

Dust and cosmic rays on the surface of the comet 67P/Churyumov-Gerasimenko on June 1, 2016, with stars moving downward in the background. Filmed by Rosetta's OSIRIS instrument.
Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, video URL: https://en.wikipedia.org/wiki/File:67P_Churyumov-Gerasimenko_surface.gif

More information

- A full timeline of solar system exploration from the 1950s until today, including many missions not mentioned here, can be found on Wikipedia:

https://en.wikipedia.org/wiki/Timeline_of_Solar_System_exploration

TV series recommendation

- For All Mankind (on Apple TV+) is an amazing TV series about the people behind space exploration.
- It's fictional but based on real historical figures.
- Very highly recommended! (100% on Rotten Tomatoes)
- Watch the trailer at this URL:

https://youtu.be/HZS9M52Bd_w

Exploration: The Sun

- Sending spacecraft close to the Sun is very hard, due to the extreme heat and radiation, which can damage the spacecraft in seconds if it's not shielded correctly.
- Helios-A was launched in 1974 and Helios-B in 1976.
  - They got within ~46.5 and ~43.5 million km of the Sun respectively.
- The Parker Solar Probe was launched in 2018.
  - It will get within ~7 million km of the center of the Sun.
  - Still very far, but Earth is ~150 million km from the Sun (1 AU) and the Sun itself has a radius of ~0.7 million km.
- It is also the fastest human-made object. At its closest approach to the Sun, in 2025, it will move at ~690,000 km/h.

The apparent size of the Sun as seen from Parker Solar Probe at perihelion (closest approach to the Sun) compared to its apparent size as seen from Earth
Credits: Maringaense (Wikipedia)

Video

- This video describes the Parker Solar Probe and some interesting discoveries made by it so far.
- The video can be found at this URL:

https://youtu.be/LkaLfbuB_6E

Origin of the solar system

- Astronomy isn't only about studying how things work in the present, it's also about figuring out their past and future.
- By observing patterns in the solar system objects, we can deduce how the system originally formed.
- For example, we know that the planets all lie on the same plane and revolve in the same direction around the Sun.
- The Sun itself also spins in the same direction around its own axis.
- This provides evidence that the Sun and planets formed together from a spinning cloud of gas and dust that we call the solar nebula.

Artist's impression of the solar nebula
Credits: NASA

Origin of the solar system

- We also know that the inner planets are composed mainly of rock and metal, while the other planets are composed of light gases and ices.
- The reason seems to be that planets closer to the Sun feel more heat. Rock and metal can survive heat, but ice and gas evaporate. The outer planets are in a much colder environment.

Origin of the solar system

- We cannot look back in time to the formation of our own solar system.
- However, we can learn about its origins by observing other planetary systems that are currently forming.
- We see many solar nebulas or circumstellar disks in our galaxy: flattened, spinning clouds of gas and dust surrounding young stars.

Planetary nurseries in the Orion Nebula as seen by the Hubble Space Telescope
Credits: Modification of work by NASA/ESA, L. Ricci (ESO)

Origin of the solar system

- We often see circumstellar disks around very young stars, suggesting that disks and stars form together.
- Computer simulations show that solid bodies can form from the gas and dust in these disks as they cool.
- The smaller objects, which are precursors of the planets, are called planetesimals.

Arrokoth, in the Kuiper belt, was the farthest object visited by a spacecraft (New Horizons) in 2019. It is composed of two planetesimals 21 km and 15 km across.
Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Roman Tkachenko.

Origin of the solar system

- Millions of small planetesimals gathered together under their mutual gravity to form the planets we see today.
- This was a violent process, with planetesimals crashing into each other.
- Due to those violent impacts, all the planets were heated until they were composed of liquid and gas.
- This allowed for differentiation, the process where the planets separate into layers of different materials.
- Heavier materials sink to form a dense central core, and lighter ones float to the surface to form a crust.

Origin of the solar system

- The solar nebula model can explain many of the regularities and patterns we find in the solar system.
- However, the random collisions of massive collections of planetesimals could be the reason for some exceptions.
- For example, Uranus and Pluto spin on their sides, and Venus spins slowly and in the opposite direction.
- This can be explained by enormous collisions that changed the planes and/or directions of their spins.

Origin of the solar system

- The formation of the solar system began ~4.6 billion years ago with the gravitational collapse of part of a giant molecular cloud.
  - Gravitational collapse is when an object collapses (shrinks in size) under its own gravity.
  - A molecular cloud is a cloud of gas, plasma, and dust which has the right density to allow for the formation of molecules like hydrogen (H_2).
- Most of the collapsing mass collected in the center, forming the Sun.
- The rest flattened into a protoplanetary disk out of which the planets, moons, asteroids, and other small bodies formed.

Origin of the solar system

- We can estimate the age of objects by observing their surfaces.
- One way to do so is by counting impact craters. This works because the rate of impacts has been roughly constant for several billion years.
- So the number of craters is proportional to the length of time the surface has been exposed.
- However, major changes in the surfaces themselves can modify or erase craters.
- Therefore, this is not a precise method. It can only tell us that a more heavily craters surface is generally older.

Origin of the solar system

- We can also measure the age of individual rocks using radioactive decay.
- Some atomic nuclei are not stable. They can decay spontaneously into smaller nuclei.
- It's impossible to predict when a decay will happen, but it is possible to predict how many decays will happen over a period of time.
- The half-life of a material is the time required for half the atomic nuclei in it to decay.

An illustration of half-life
Credits: OpenStax Astronomy

Origin of the solar system

- If I have 1 kg of a radioactive material with a half-life of 100 years:
  - After 100 years, I will have 1/2 kg.
  - After 200 years, I will have 1/4 kg.
  - After 300 years, I will have 1/8 kg.
  - After 400 years, I will have 1/16 kg.
  - And so on.
- However, the material does not disappear. Instead, the radioactive atoms are replaced with their decay products.
- By comparing the quantity ratio of a radioactive element to its decay products in a rock, we can learn how long ago it was formed.

- Here are some examples of radioactive elements used to date rocks.
- The number after each element is its atomic weight, the number of protons plus neutrons in its nucleus.
- This specifies the isotope of the element. Different isotopes have the same number of protons but a different number of neutrons.

Radioactive Element	Decay Product	Half-Life (billions of years)
Samarium-147	Neodymium-143	106
Rubidium-87	Strontium-87	48.8
Thorium-232	Lead-208	14.0
Uranium-238	Lead-206	4.47
Potassium-40	Argon-40	1.31

Origin of the solar system

- With radioactive dating, it was determined that the age of Earth is ~4.5 billion years.
- Radioactive dating was also performed on rocks brought back by astronauts from the Moon. It turns out the Moon formed around the same time as Earth.

Conclusions

- In this lecture, we learned about our home, the solar system, and many of the objects in it.
- We will continue learning about it in more details in the next lecture.

- Reading: OpenStax Astronomy, chapter 7.
- Exercises: Practice questions will be posted on Teams.