Robotic Exploration of the Solar System – From Mercury to Pluto

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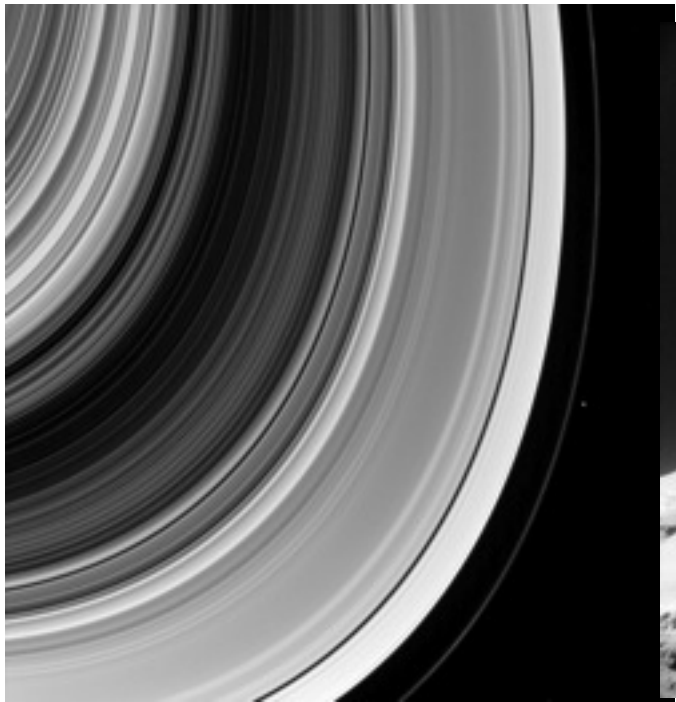
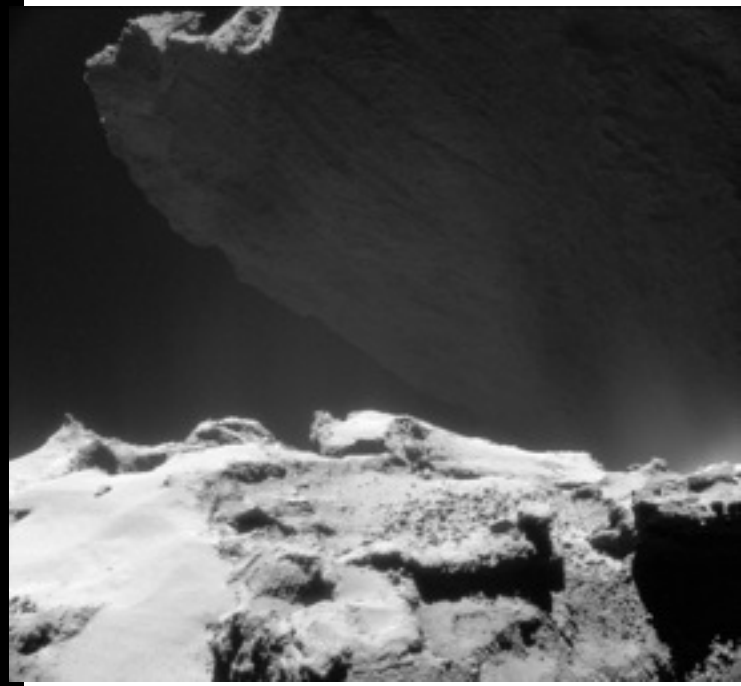
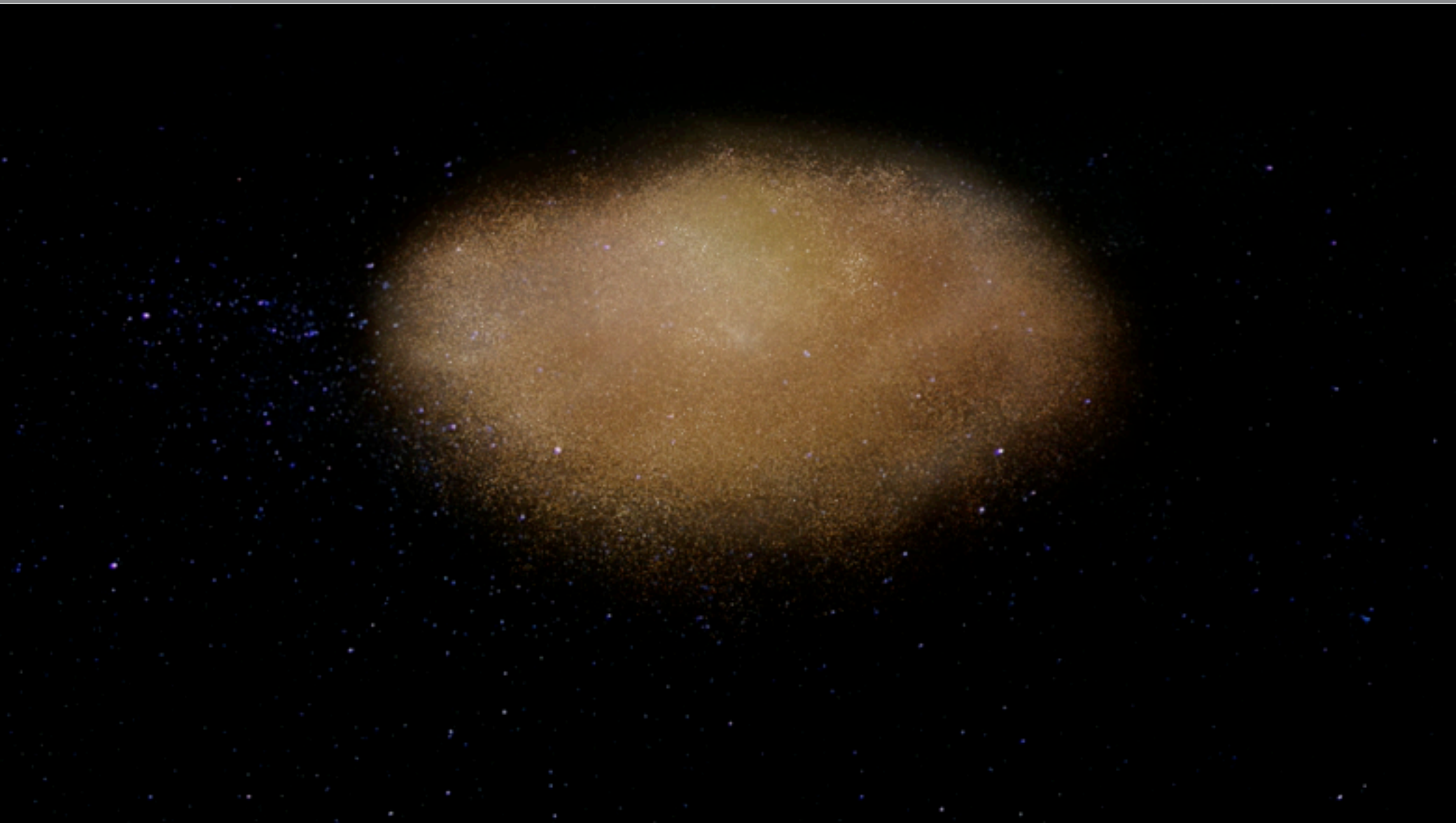
1. Formation and Characteristics of the solar system
2. Exploration over time
   - Terrestrial Planets
   - Giant planets
   - Dwarf planets and small bodies
3. Conclusions





Solar system formation



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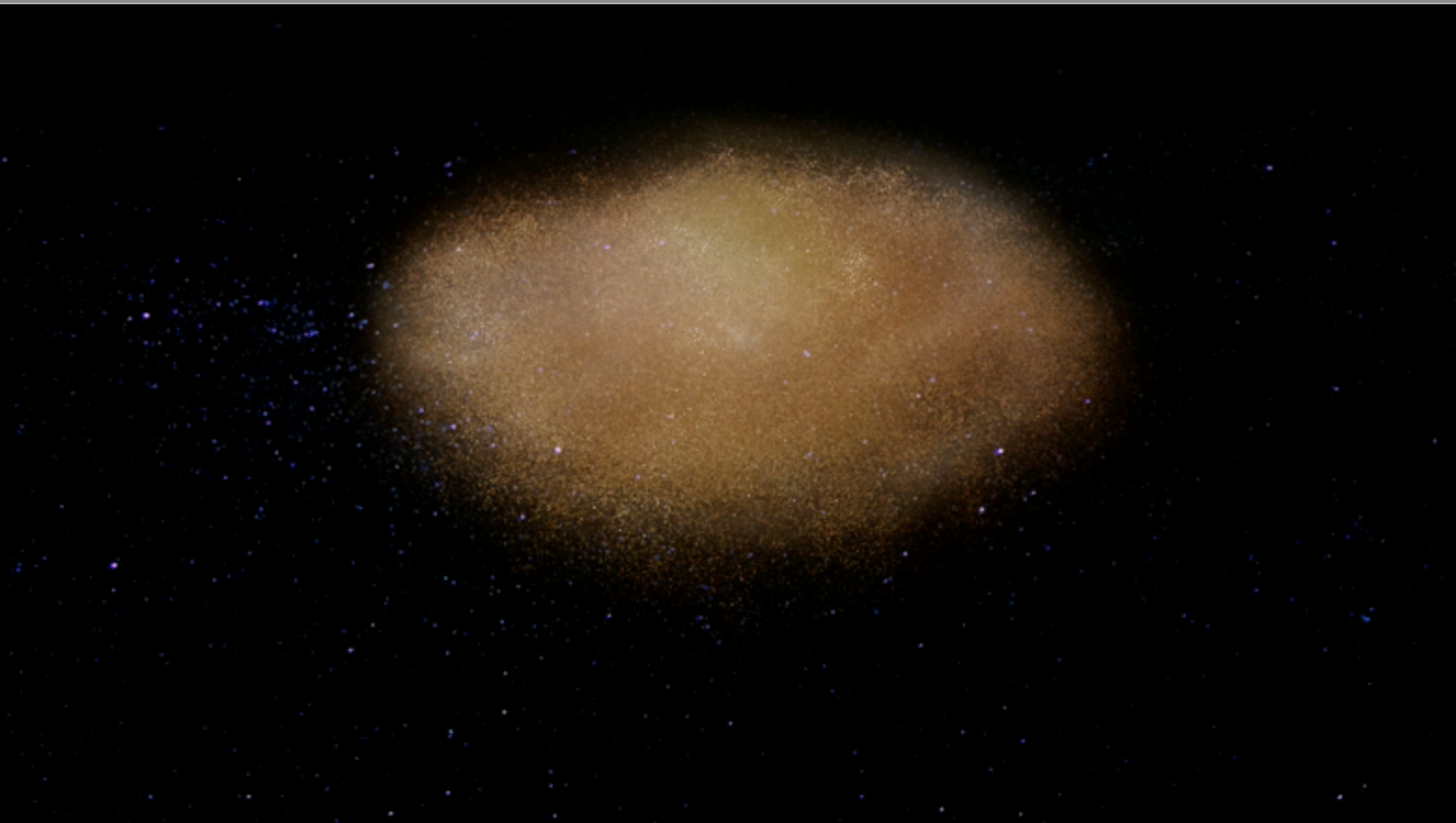

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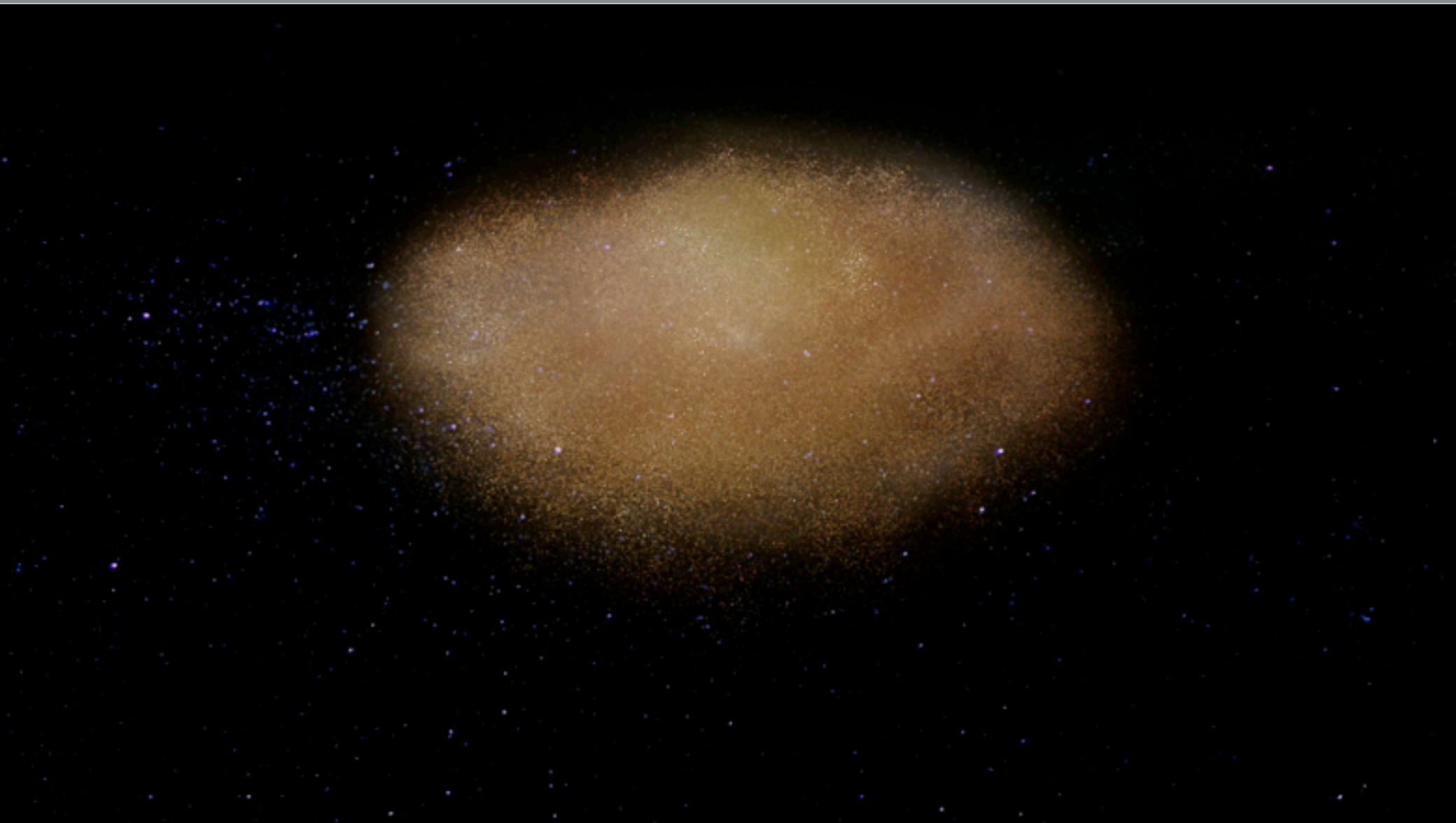
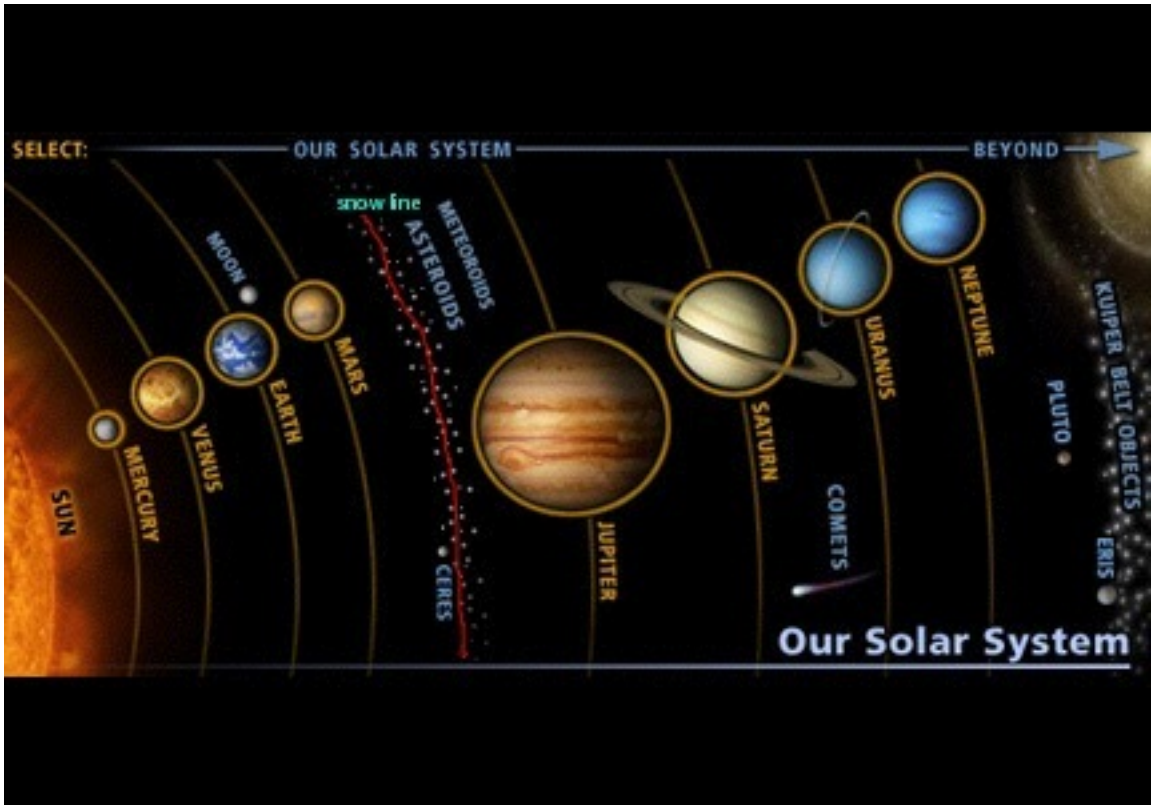


Solar system today

- Terrestrial planets
  - ➢ Earthlike
  - ➢ Formed dry (?)
  - ➢ Formed without moons
  - ➢ Processed
  - ➢ Water
  - ➢ Habitability
  - ➢ Atmospheres
  - ➢ Life
- Giant planets
  - ➢ Icy
  - ➢ Miniature solar systems
  - ➢ Processed (partly)
  - ➢ Atmospheres
  - ➢ Liquid water ?
  - ➢ Habitability of some moons?

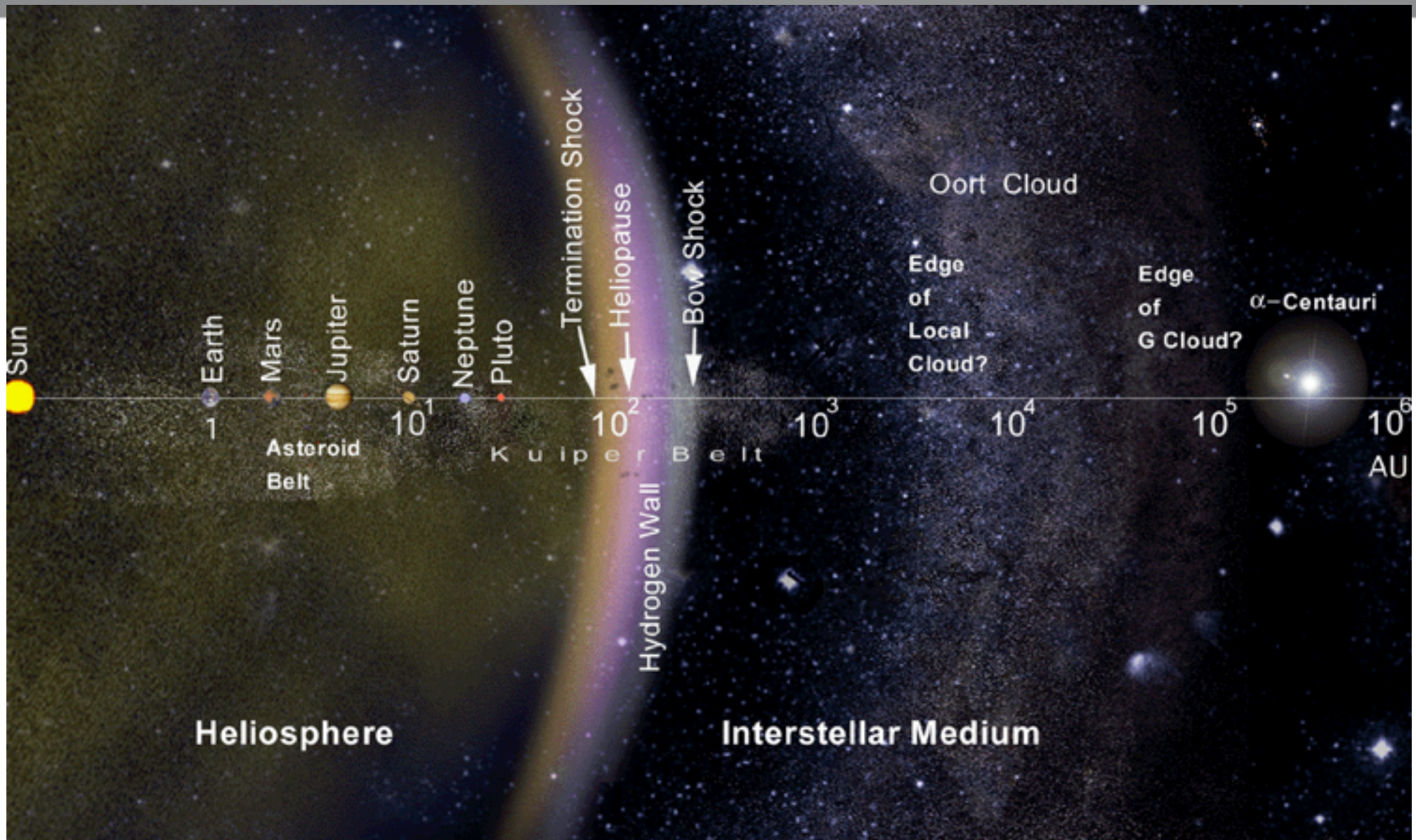
Planet: Round and has "cleaned its neighborhood"



Source: Wikipedia

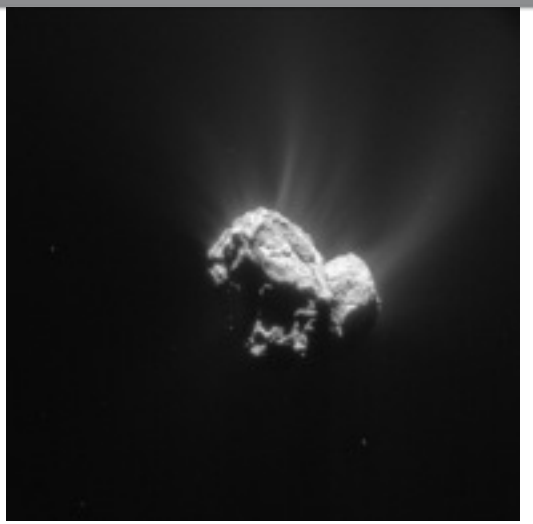
Solar system today (2)

Source: Wikipedia

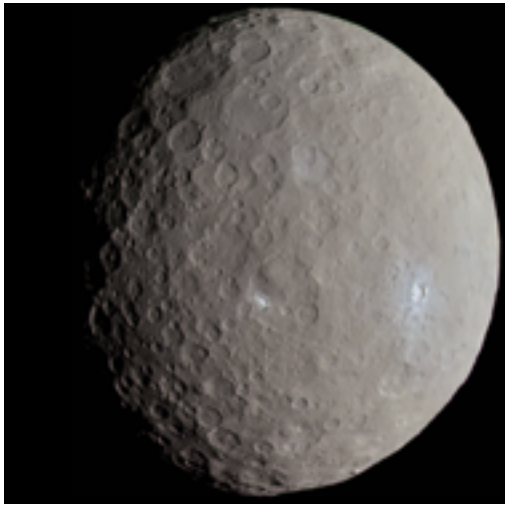


Solar system today (3)

- Small bodies (Asteroids and Comets)
  - Remnants of solar system formation
  - Least processed objects, "time machines"
  - Brought water to Earth?
  - Role in formation of life on Earth?
- Dwarf planets
  - Round objects that did not clean their neighborhood
  - One in the asteroid belt (Ceres)
  - Currently four in the Kuiper belt (Pluto, Eris, Haumea, Makemake)

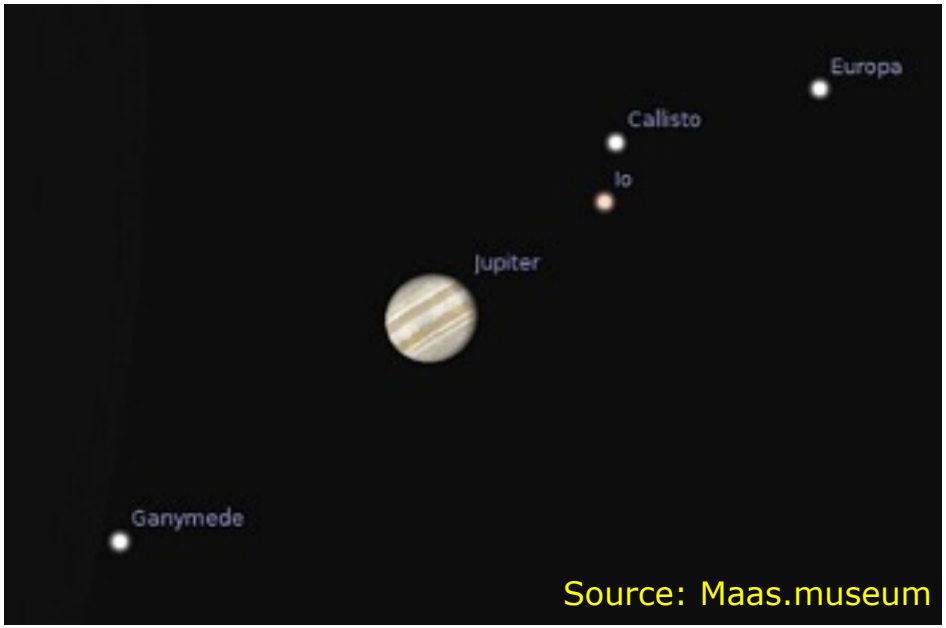


Comet C/G imaged by Rosetta

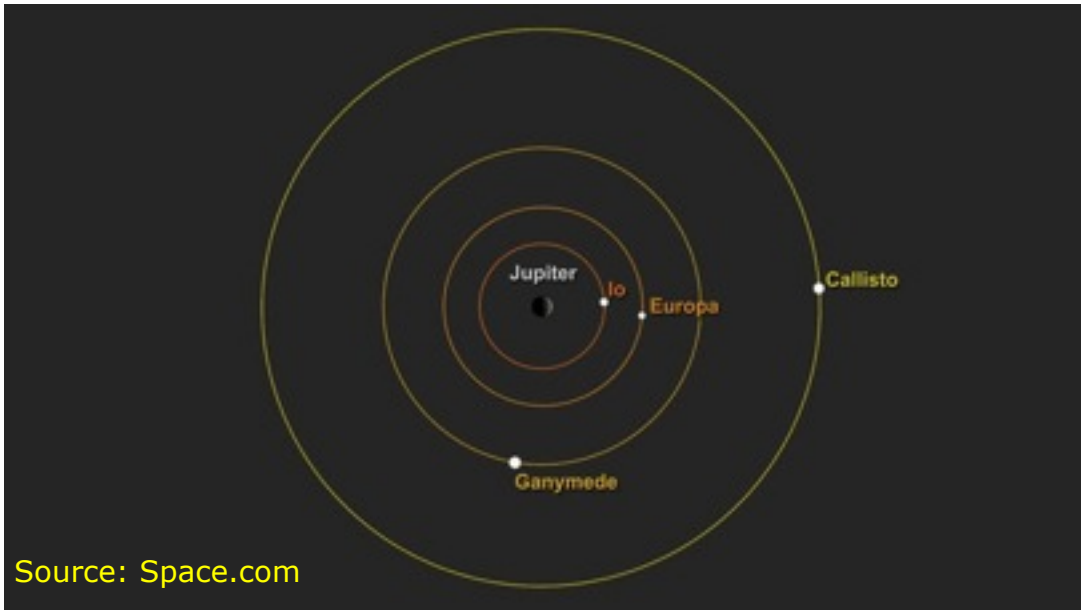


Ceres imaged by DAWN

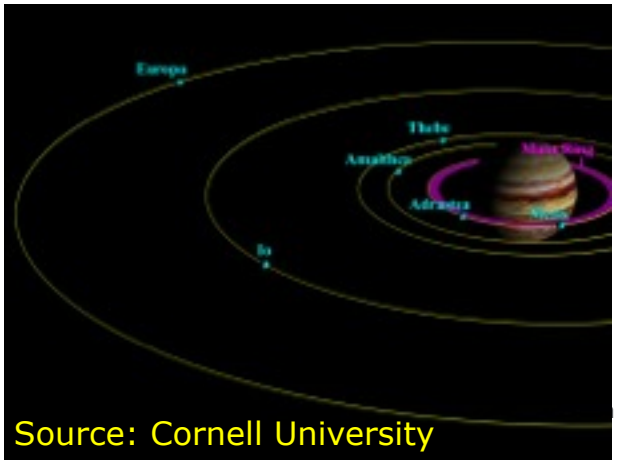
Example of a "mini solar system": Jupiter



Source: Maas.museum

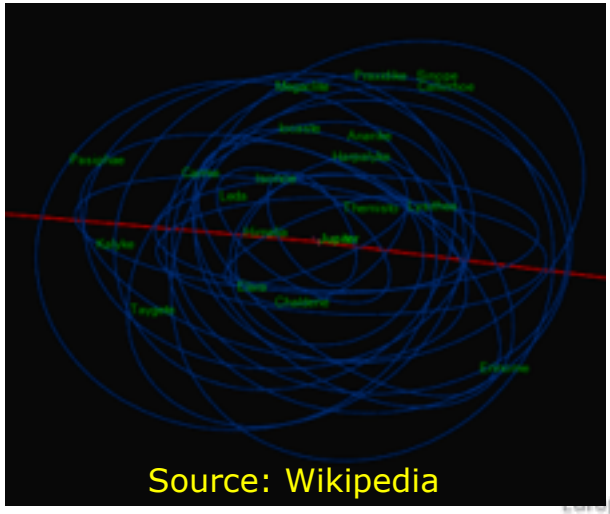


Source: Space.com



Source: Cornell University

67 moons in total!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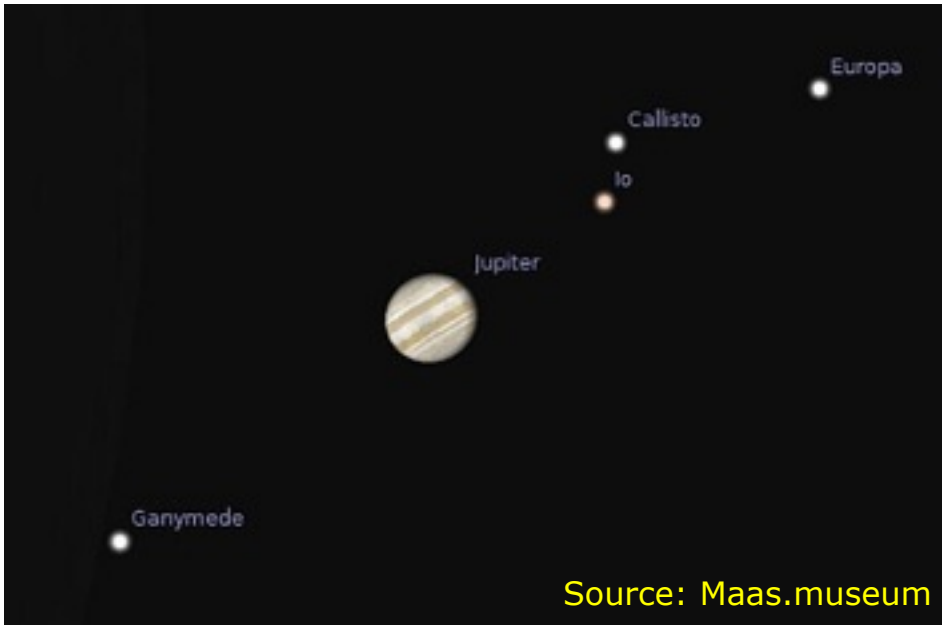

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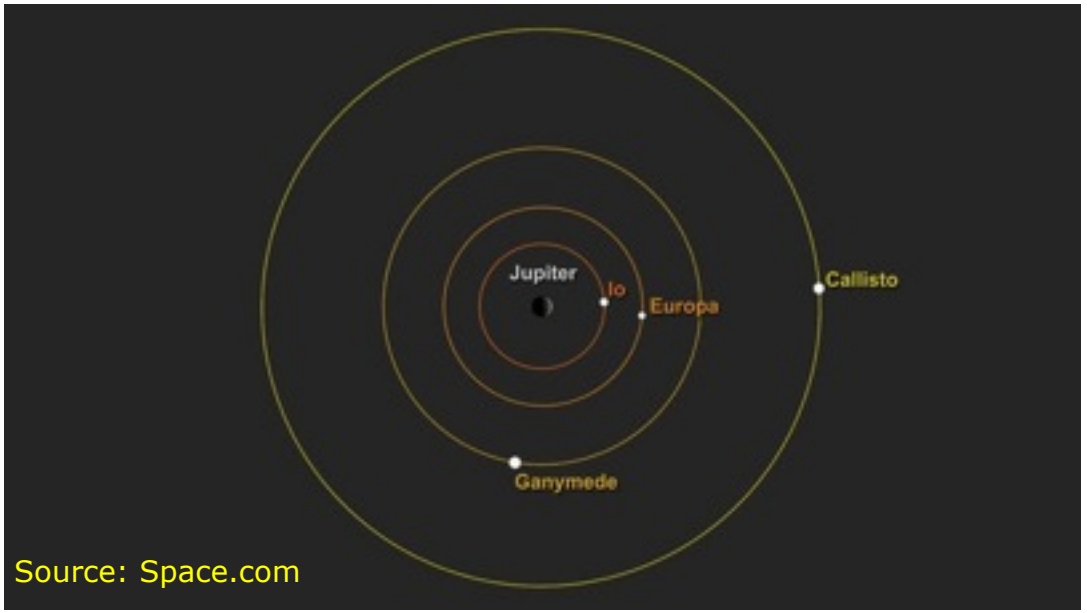

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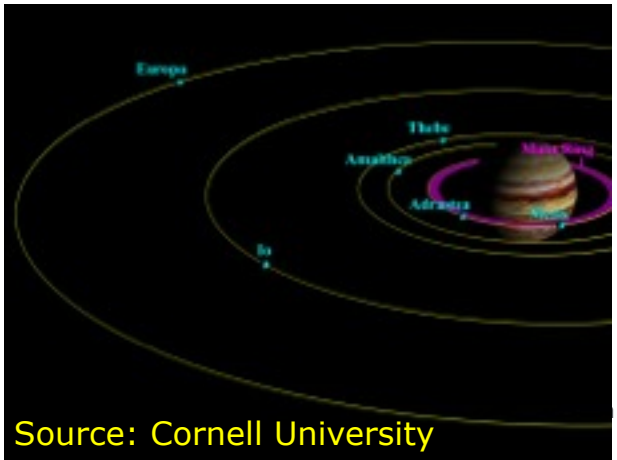

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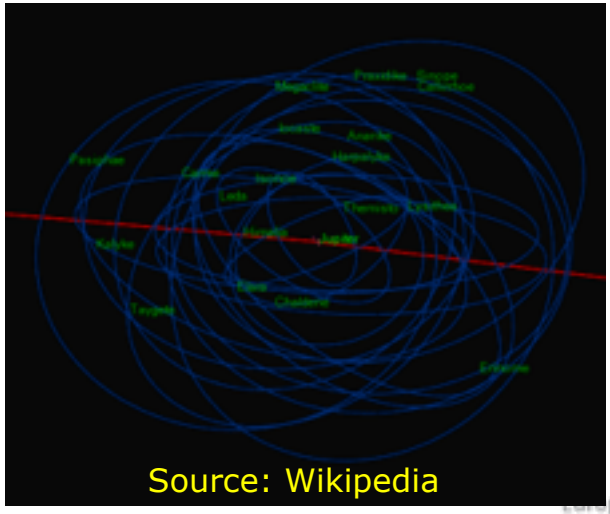
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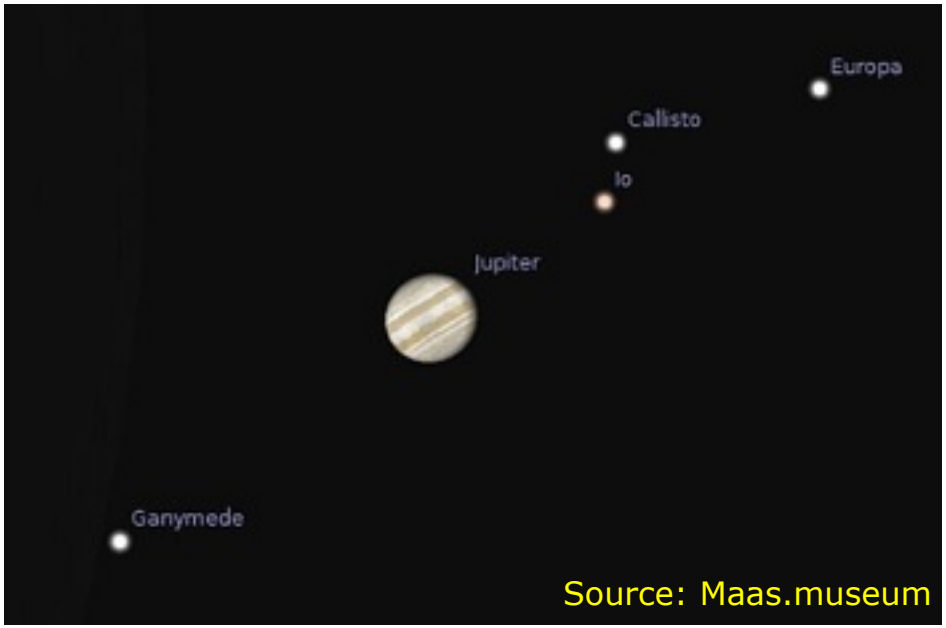

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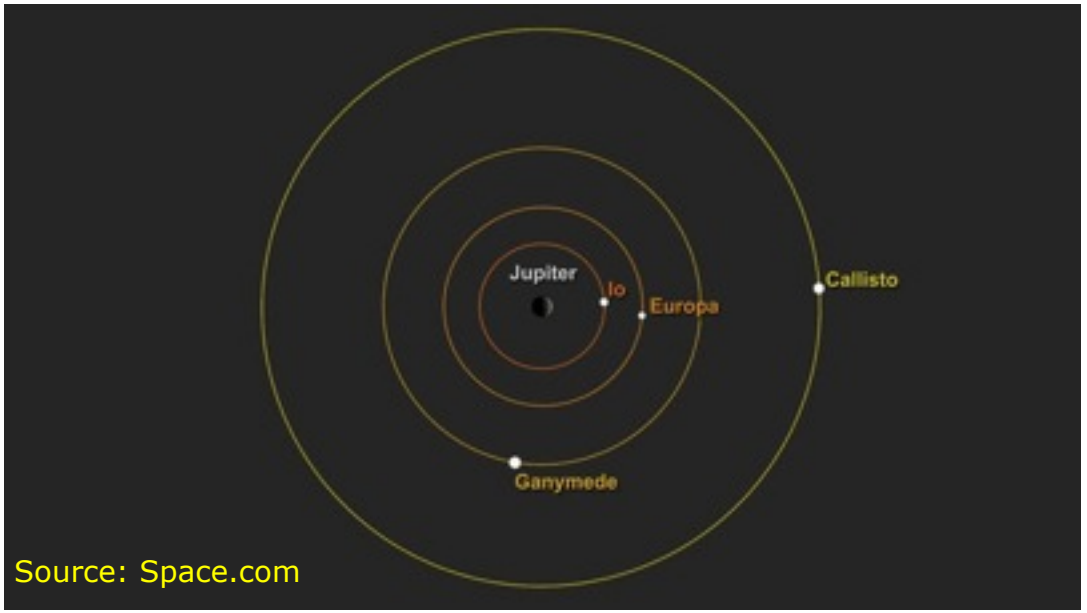

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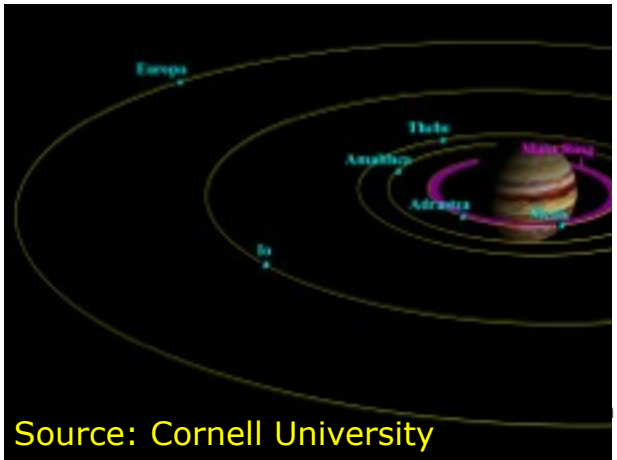

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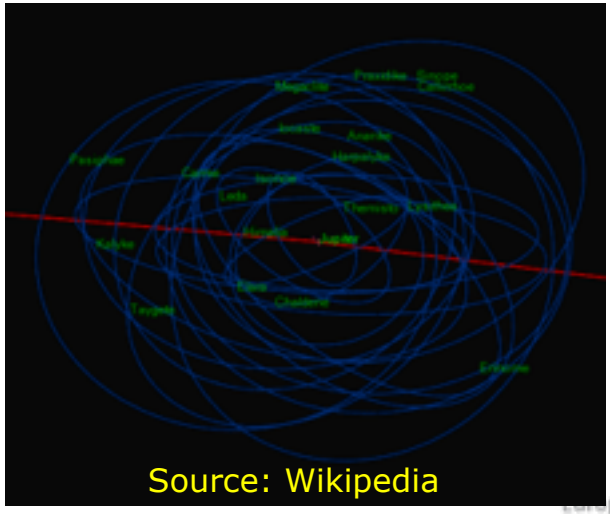
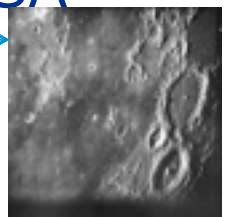

Source: Wikipedia

Interplanetary Exploration

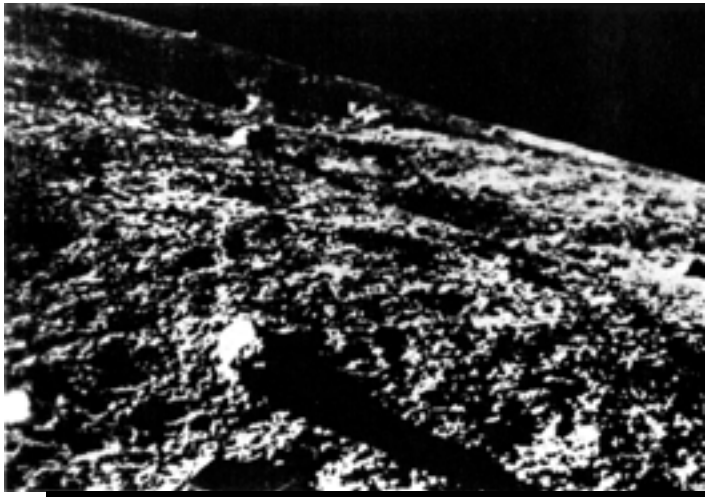
Terrestrial planets: Exploration of the moon

- **The moon:** Telescopic object until 1959
- **1959:**
  - First flyby 4 January (Luna 1, intended impact, first interplanetary spacecraft)
  - First impact 14 Sept. (Luna 2)
  - First image of the far side 6 October (Luna 3)
- **1961:** John F. Kennedy speech
- **1964:** First image from the moon taken from a NASA spacecraft (Ranger 7)



Exploration of the moon: Towards manned landing

- **1966**:
  - First controlled landing (Luna 9)
  - First lunar orbiter and first investigations of the nature of lunar rocks (Luna 10)
- **1968**:
  - First lunar spacecraft successfully recovered after flyby (Zond 5)
  - First manned orbiter (Apollo 8)
- **1969:** First manned landing and first sample return (Apollo 11)

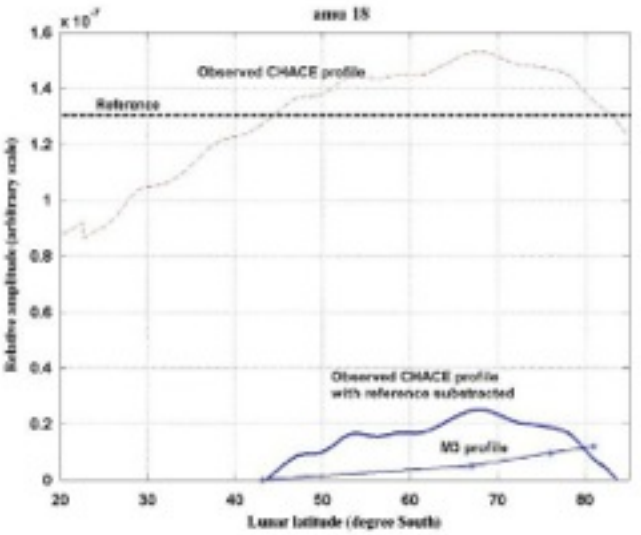


Lunar exploration after Apollo 11

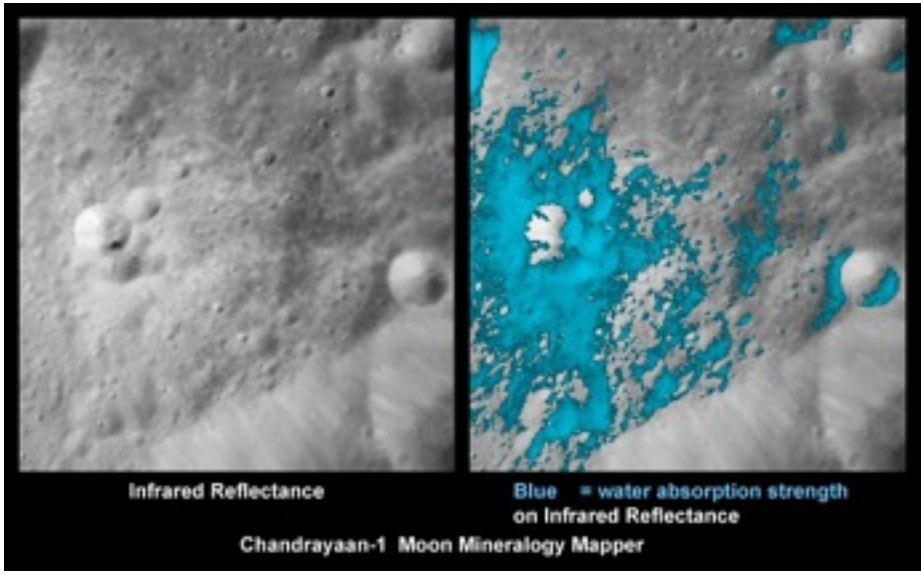
- **1970:** First lunar rover (Luna17 –Lunokhod 1)
- **1972:** Last Apollo mission (last manned mission to the moon)
- **1973:** Last NASA mission to the moon for >20 years (Mariner 10, imaging of the north pole)
- **1976:** Last mission to the moon from the Soviet Union (Luna 24 sample return)

Lunar exploration: Development 1990 - today

- High resolution imaging and spectroscopy with modern instrumentation
  - Detection of water ice at near-polar areas (Chandrayaan-1)
  - Global mapping at high resolution (LRO)
- Lunar missions by several nations
  - Japanese Hiten and Kaguya orbiter 1990/2007
  - ESA's SMART-1 orbiter 2003
  - Chinese Chang'e program: orbiters 2007/2010) and lander and rover (2013)
  - Indian Chandrayaan-1 orbiter and impactor (2008)

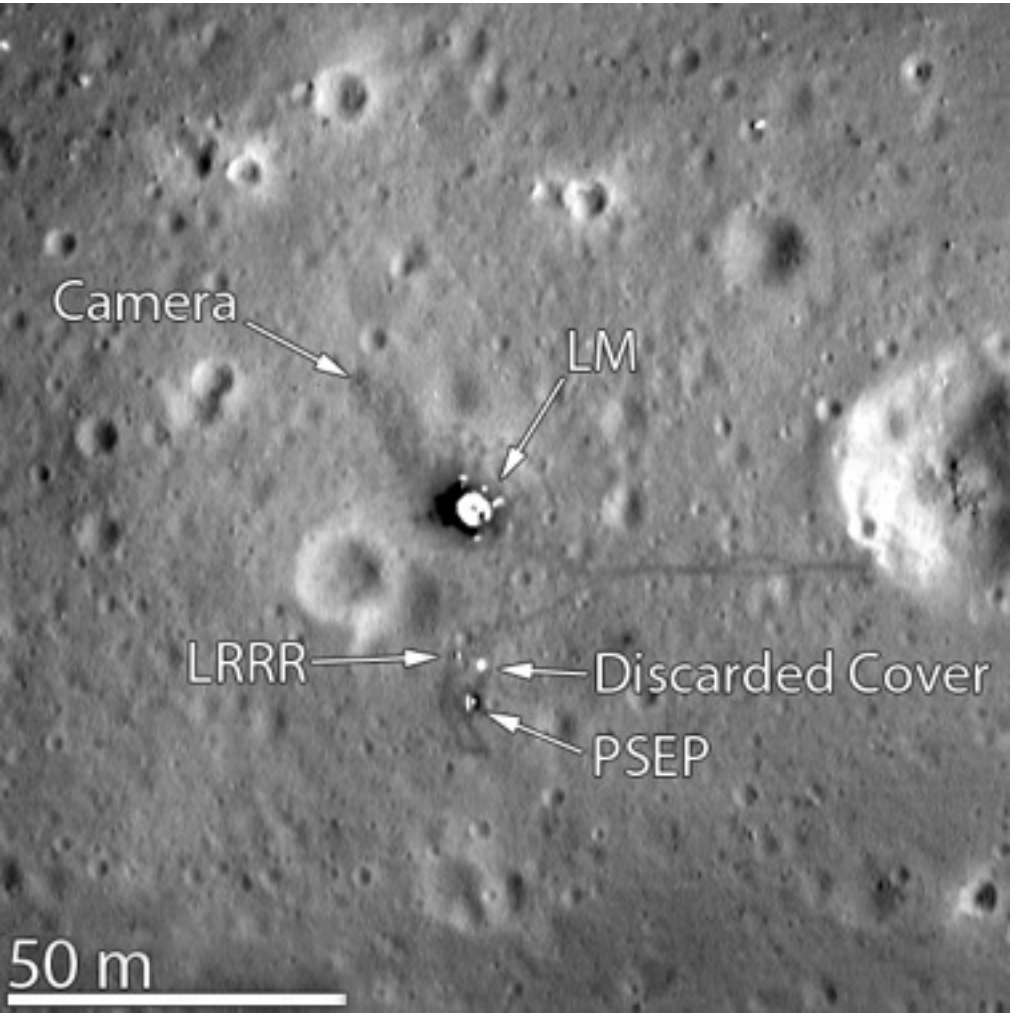


Latitudinal variation in amu-18 measurement by CHACE, Chandrayaan-1 Moon Impact Probe

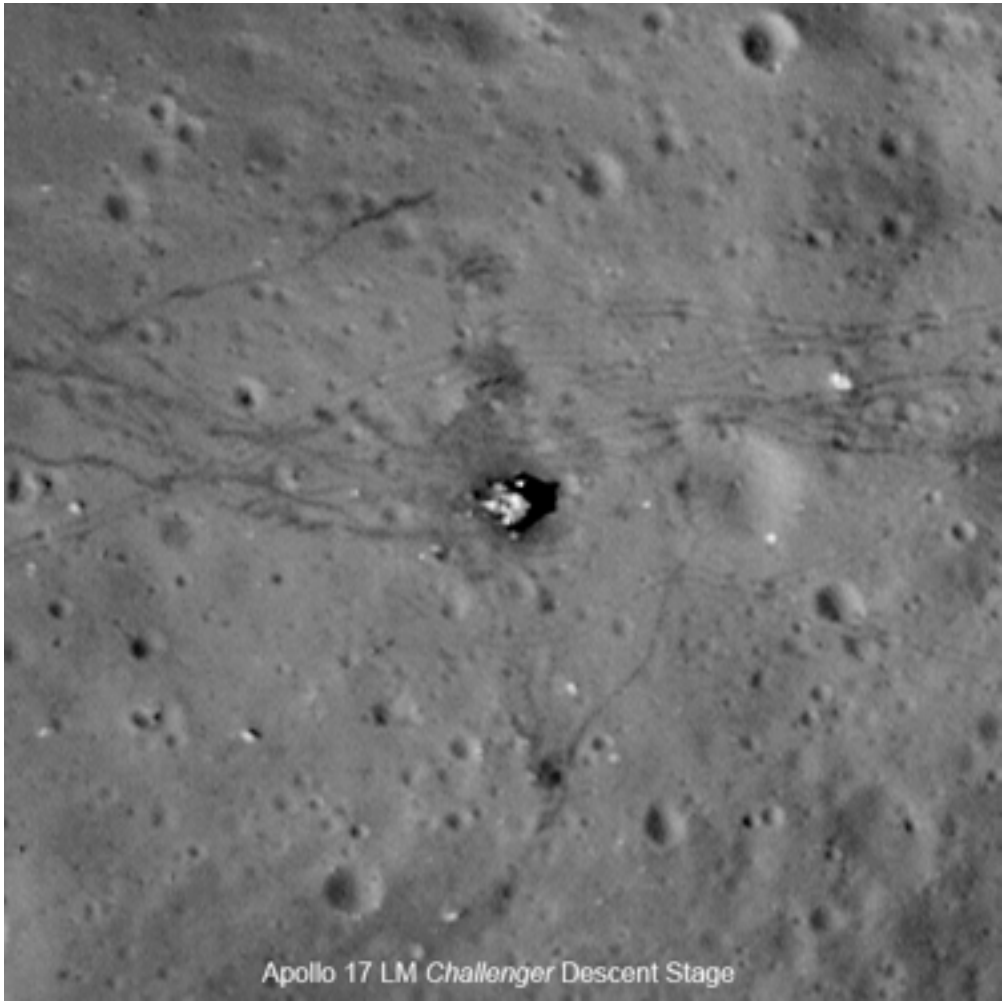


Landing sites with Lunar Reconaissance Orbiter (LRO)

Apollo 11



Apollo 17

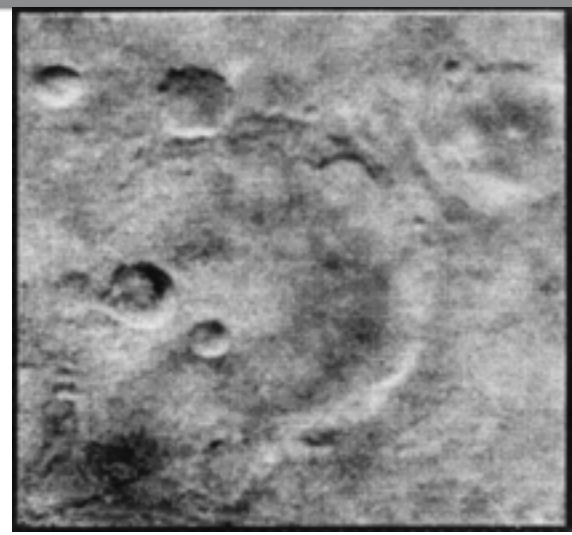


Future of lunar exploration

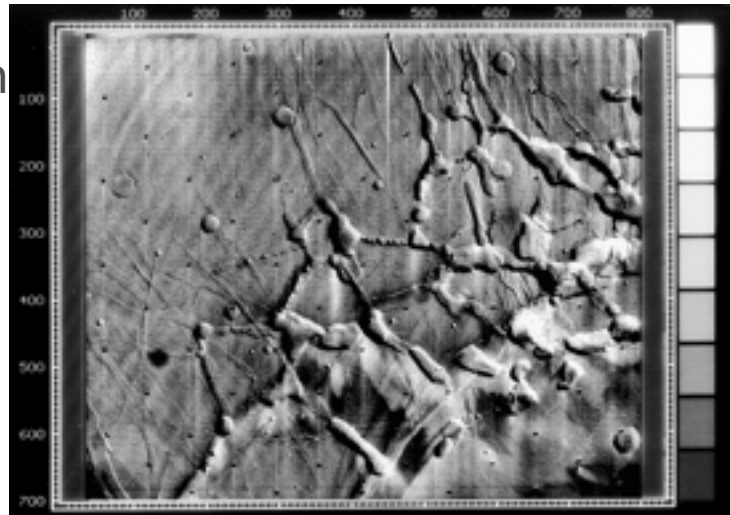
- Private missions: Google lunar X-prize
  - 30 million $ for private initiative who operates a rover on the moon
  - Three competitors foresee common launch in 2017 (with private Falcon-9 launch vehicle)
- Chinese sample return mission foreseen in 2017
- Various orbiters and lander in the next years
- ESA's "moon village" concept

- Return of humans to the moon in 2025+ ???

Exploration of Mars

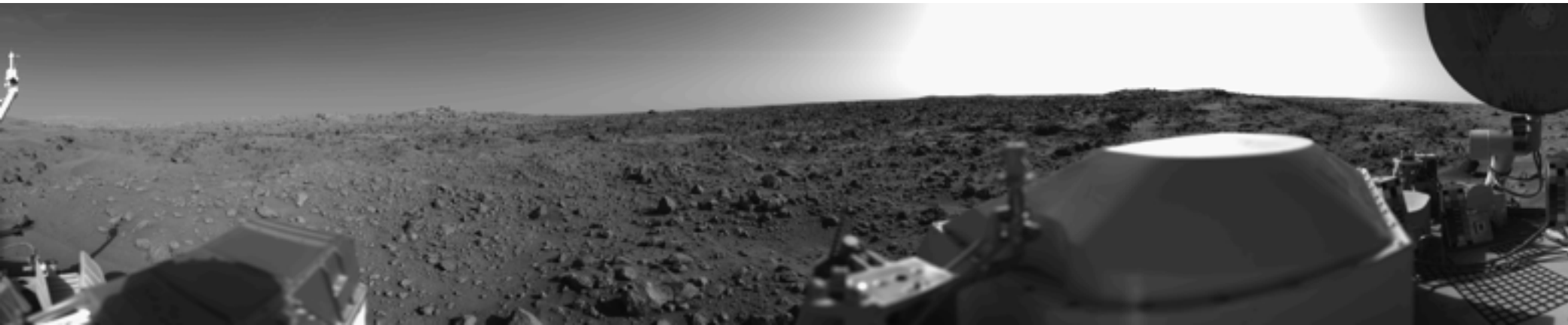


- **1964:** First flyby of Mars (Mariner 4)
  - Showed moon-like surface (not typical)
  - Measured atmospheric pressure and temperature
- **1969:** Mariner 6 and 7 show absence of "canals"
- **1971:** First orbiter around a planet other than Earth (Mariner 9)
  - Arrived during dust storm that obscured view on ground
  - Mapped 85 % of the surface
  - Detected huge (extinct) volcanoes and valleys



Landing on Mars

- **1971:** First soft landing on Mars (Mars 3)
  - Contact for ~15 s
- **1975:** Viking orbiters and landers
  - First clear images from Mars surface
  - Search for life => inconclusive!
  - Last successful Mars mission in > 20 years!



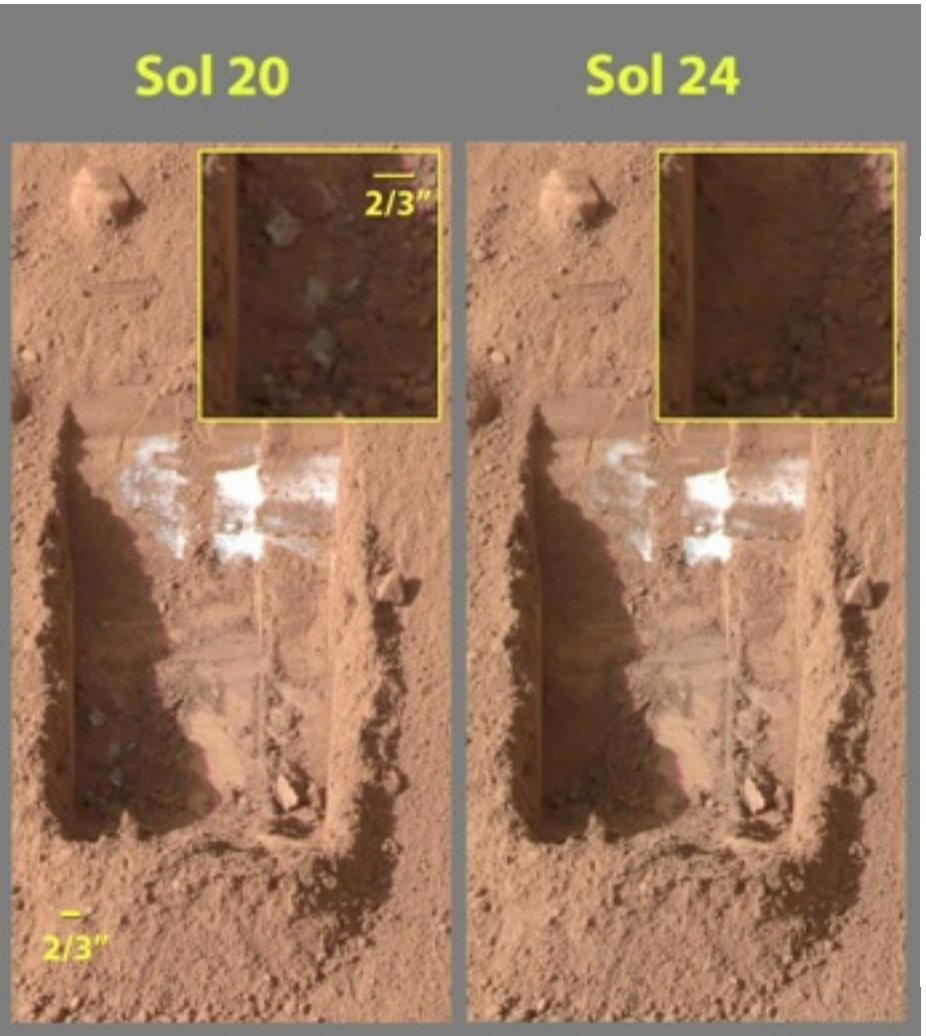
Phobos observed by Viking: First images of an asteroid?

Mars exploration 1990s – today

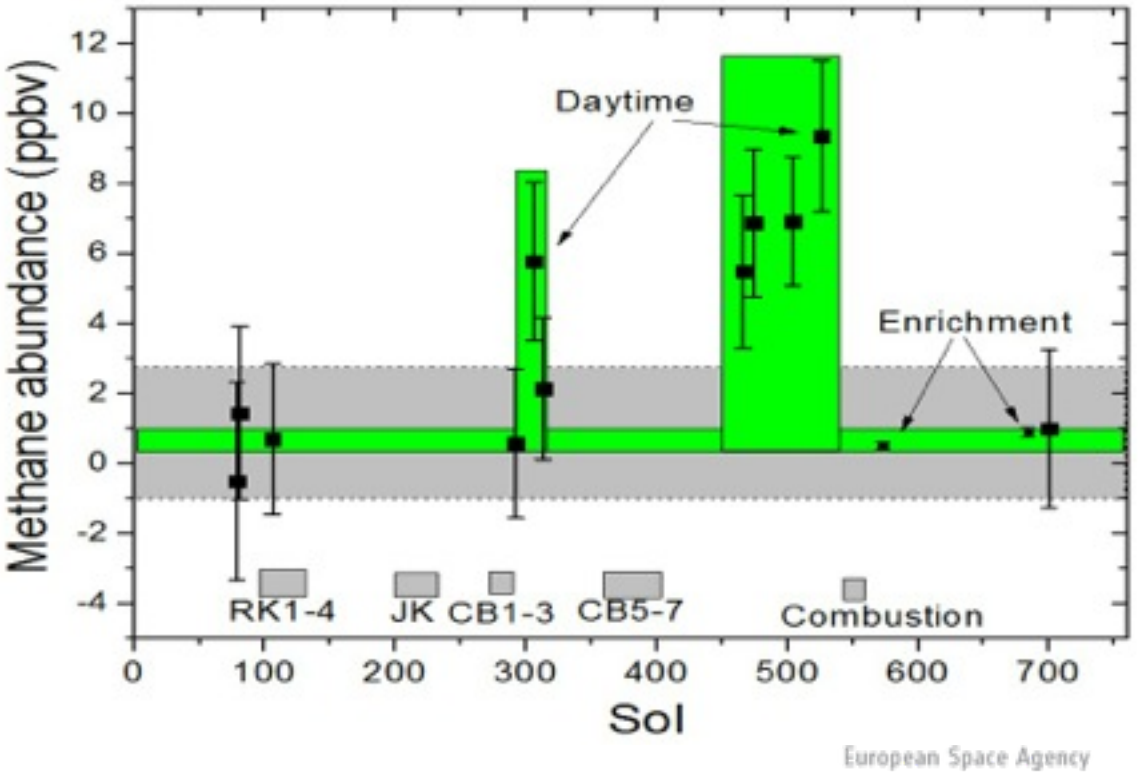
- Global mapping, spectroscopy, topography, gravity field, crustal magnetic field
  - Several orbiters by NASA, ESA, India (currently 5 operational + Exomars on route)
- Lander and Rover provide (sub) surface properties, composition, search for life
  - Several lander by NASA, currently two opertional
- Evidence for water ice found by multiple spacecraft
  - Ground truth by Phoenix lander in 2007
- Methan found on Mars
  - Biologically relevant
  - Can also be created abiologically

Discoveries on Mars

Water ice



Methane



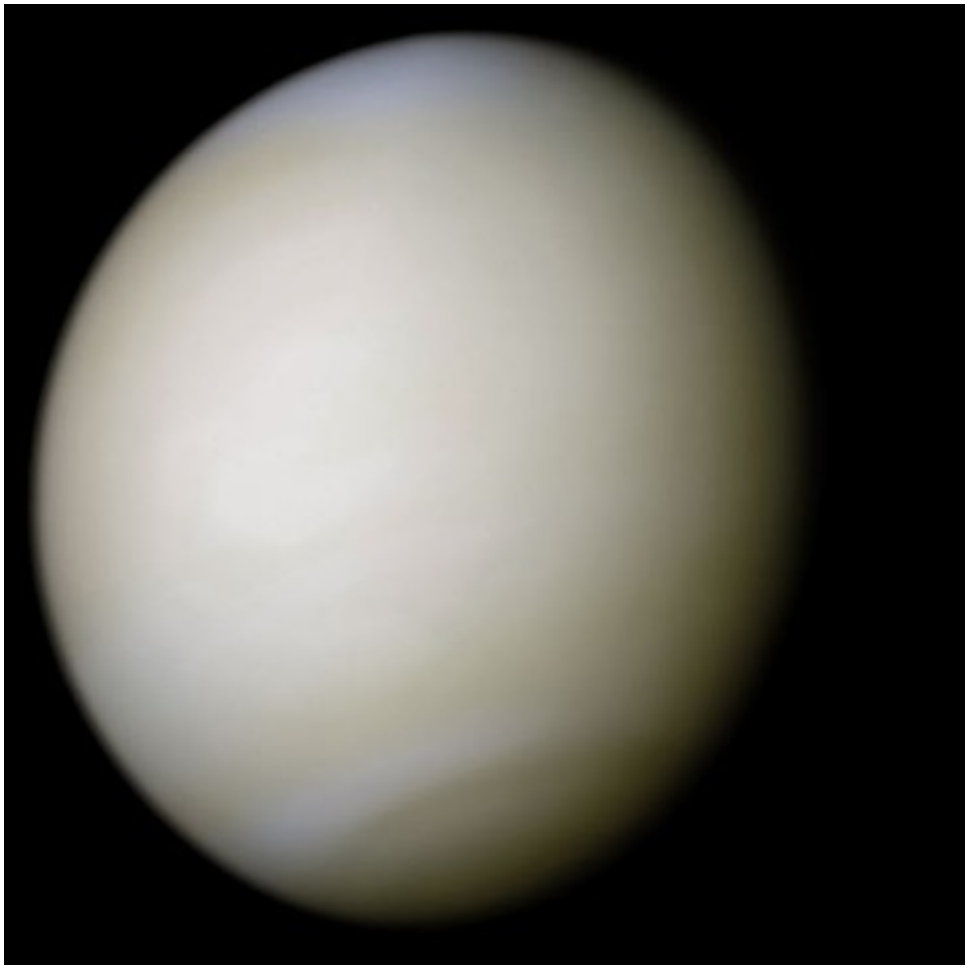
Future of Mars exploration

- First private Mars mission foreseen for 2018 (red dragon lander by SpaceX)
- Several new orbiters, landers and rovers
  - ESA's Exomars rover will search for life, with more sensitive instrumentation than Viking
- Phobos sample return mission

  to be launched in 2022 (TBC)
- Mars sample return 2025+ ?
- Manned mission to Mars 2040+ ?

Exploration of Venus

Venus in visible light



Radar view of Venus

Missions to Venus

- **1962:** First successful planetary flyby (Mariner 2)
  - Investigation of Venus atmosphere (esp. temperatures)
- **1969:** In situ measurements of the atmosphere with Venera 5 and 6 atmospheric probes
- **1972**: First successful landing on Venus (Venera 8)
- **1975**: First orbiter and first images from surface(Venera 9 and 10)

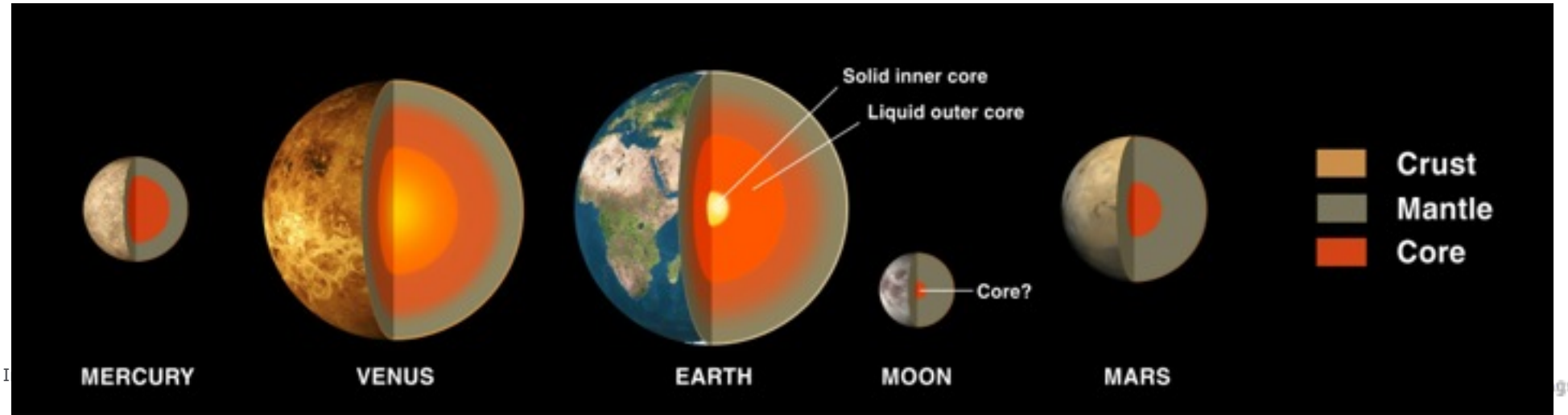
Missions to Venus (2)

- **1989**: Magellan: First radar map of Venus surface
- **2005**: ESA's Venus express orbiter
  - Detection of volanism
- **2010:** Japanese Akatsuki mission
  - Orbit insertion Dec. 2015 on second attempt
  - Venus flyby by Icarus solar sail technology demonstration

Missions to Mercury

- Mariner 10 (3 flybys in 1974/75)
  - Moonlike surface
- Little interest in the following decades

But: Why is Mercury's core so large?



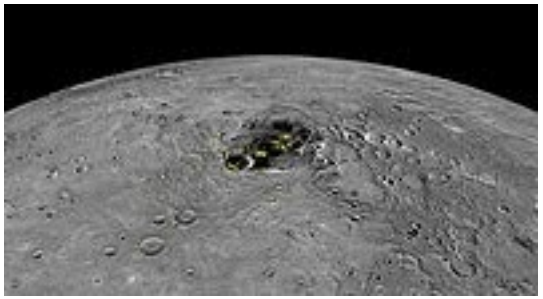
How did Mercury form with a large core to mantel ratio?

Mantle stripped away (e.g. impact)

Formed from mostly matellic material

New missions to Mercury

- Messenger (launch 2004, several flybys of Venus and Mercury, in orbit 2012-2015)
  - Much compositional (and other information)
  - Discovery of water and past volcanic activity
  - Not completely conclusive about formation

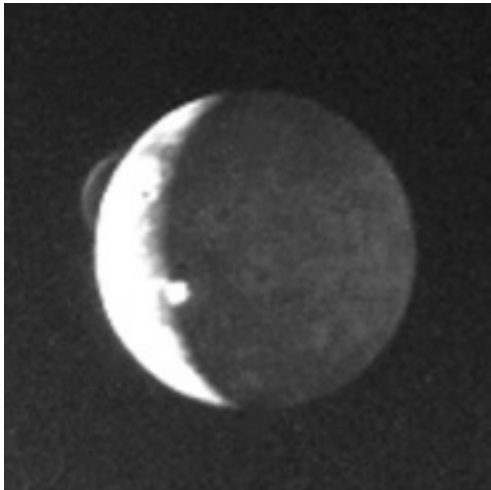


- Bepi-Colombo (ESA Planetary Orbiter + NASA Magnetospheric Orbiter)
  - Launch 2018, arrival 2024
  - More sophisticated instrumentation than Messenger

Exploration of giant planets: Jupiter

- Flyby missions:

1. Pioneer 10 and 11 (1973/74)
   - First close images of Jupiter and the Galilean Satellites
   - Detection of magnetic field
2. Voyager 1 and 2 (1979)
   - Active volcanoes on Io
   - Jupiter rings
3. Ulysses (1992)
4. Cassini (2000)
5. New Horizons (2007)



Exploration of Jupiter

➢ Orbiter missions

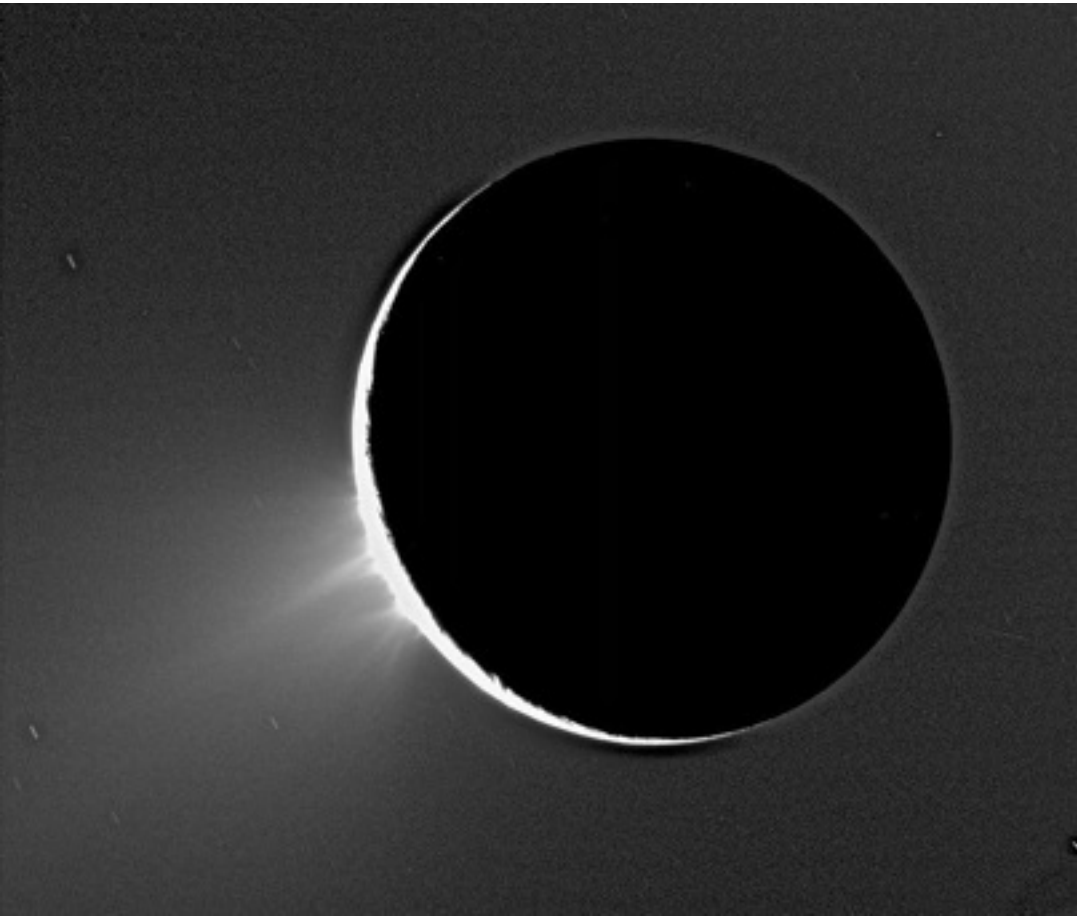
1. Galileo (1995-2003)
   - Jupiter orbiter and atmospheric probe
   - Numerous flybys of Galilean moons
   - Detected evidence for subsurface ocean on Europa and maybe Ganymed and Callisto
2. Juno (2016)
   - Orbiter studying composition and magnetic field of Jupiter
3. JUICE (launch 2022, arrival 2030)
   - ESA Ganymed orbiter (+ flybys of Europa and Callisto)
4. Europa orbiter proposed to NASA
   - Timescale would be similar to JUICE

Exploration of Saturn

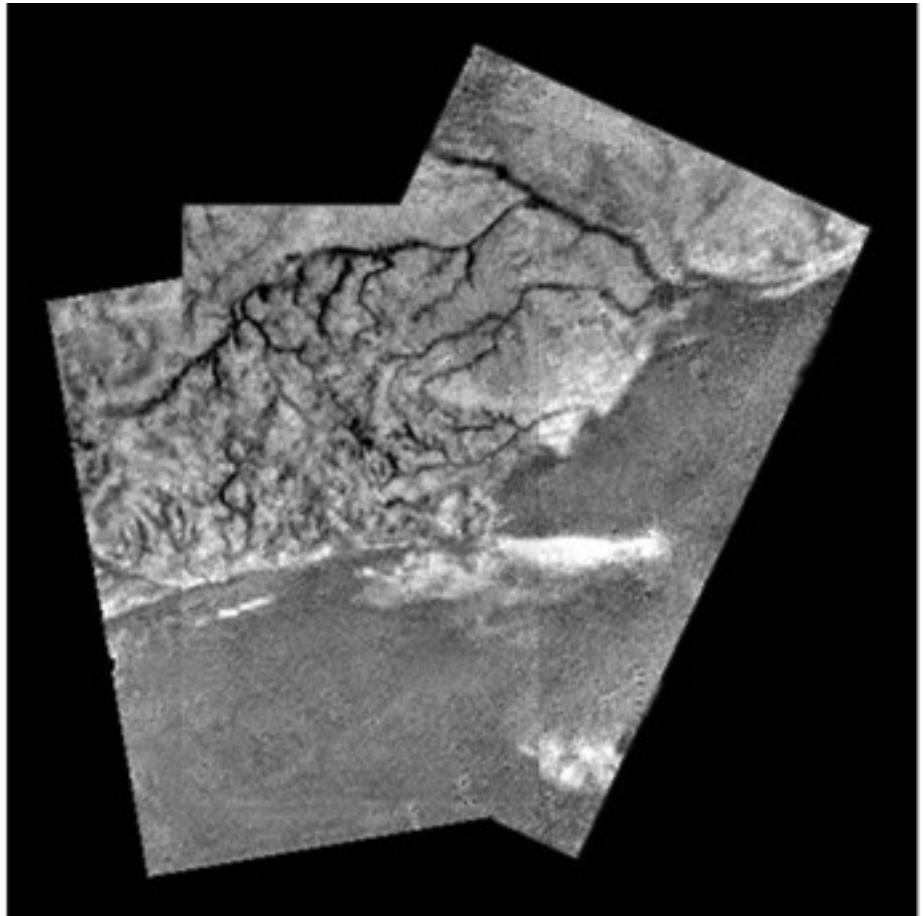
- Pioneer 11 flyby in 1979
  - Detected new, faint ring (F-ring)
- Voyager 1 and 2 flybys in 1980 and 1981
  - First high resolution images of Saturn and its satellites
- Cassini-Huygens orbiter (2004-2017)
  - Orbiter with multiple flybys of main satellites
  - Titan lander
  - Discovered landscape on Titan shaped by liquids
  - Discovered activity on Enceladus (and potential for subsurface ocean)

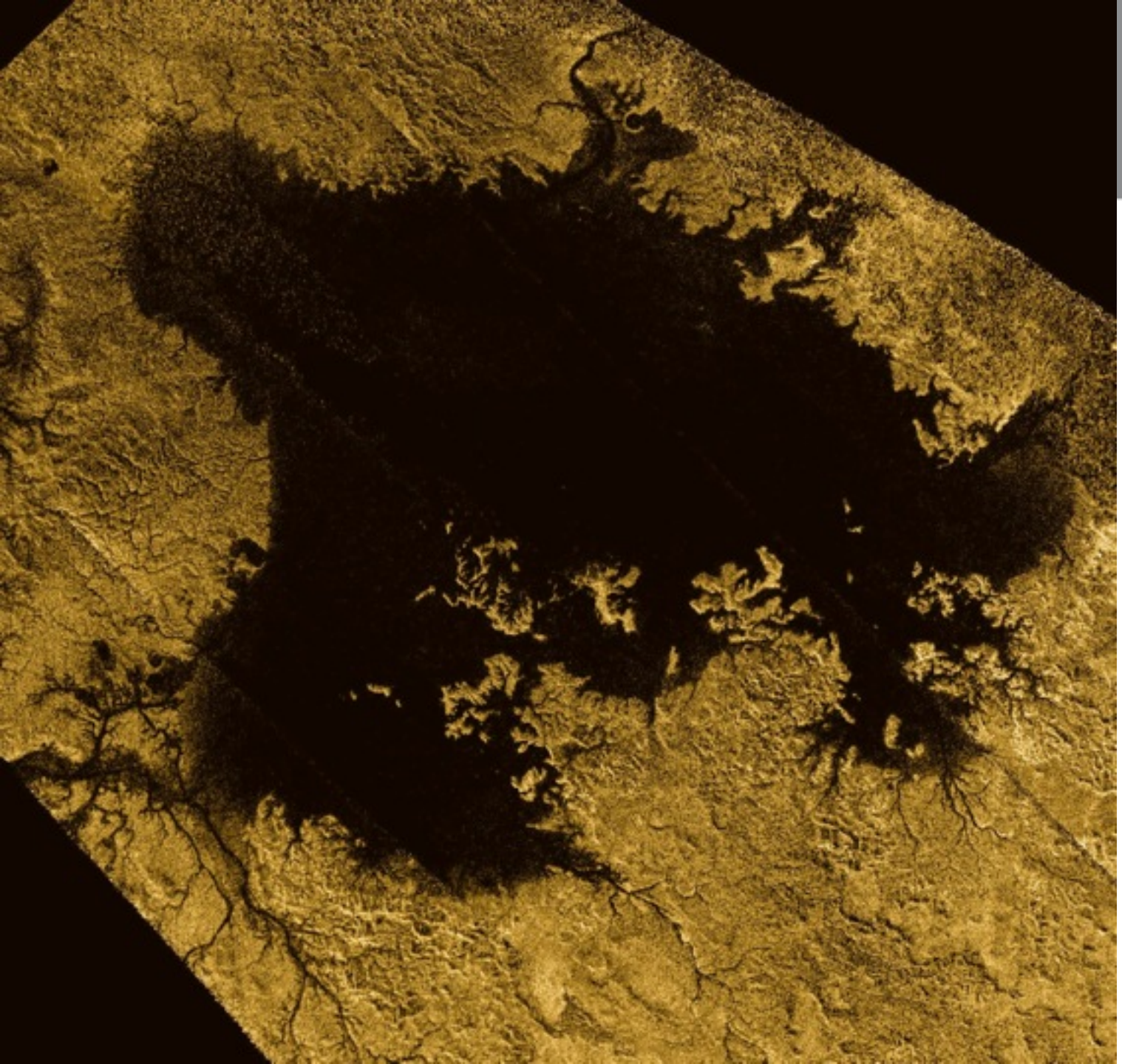
Cassini-Huygens discoveries

Plumes on Enceladus



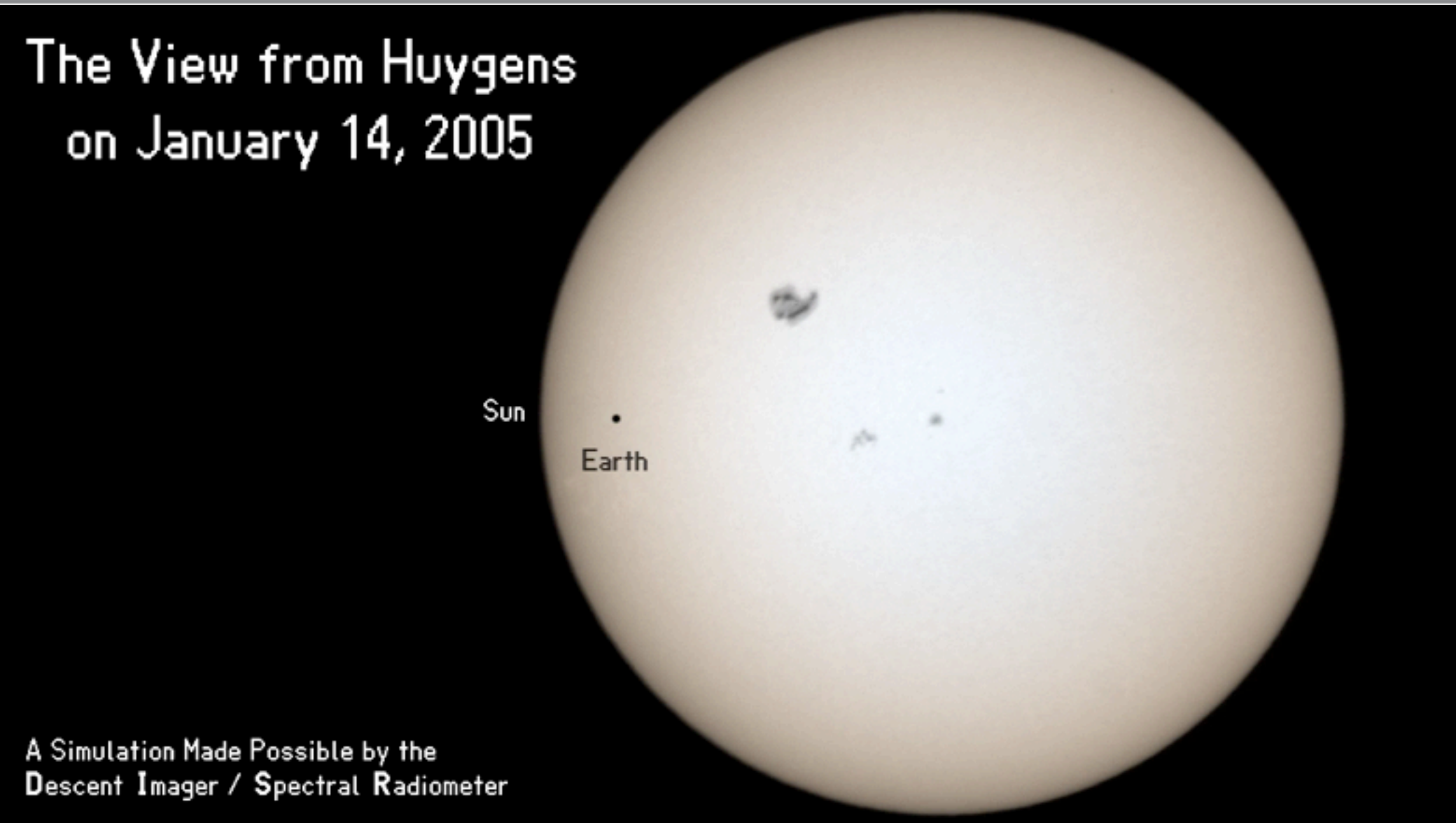
River channels on Titan





Hydrocarbon lake on Titan

Huygens descent on Titan



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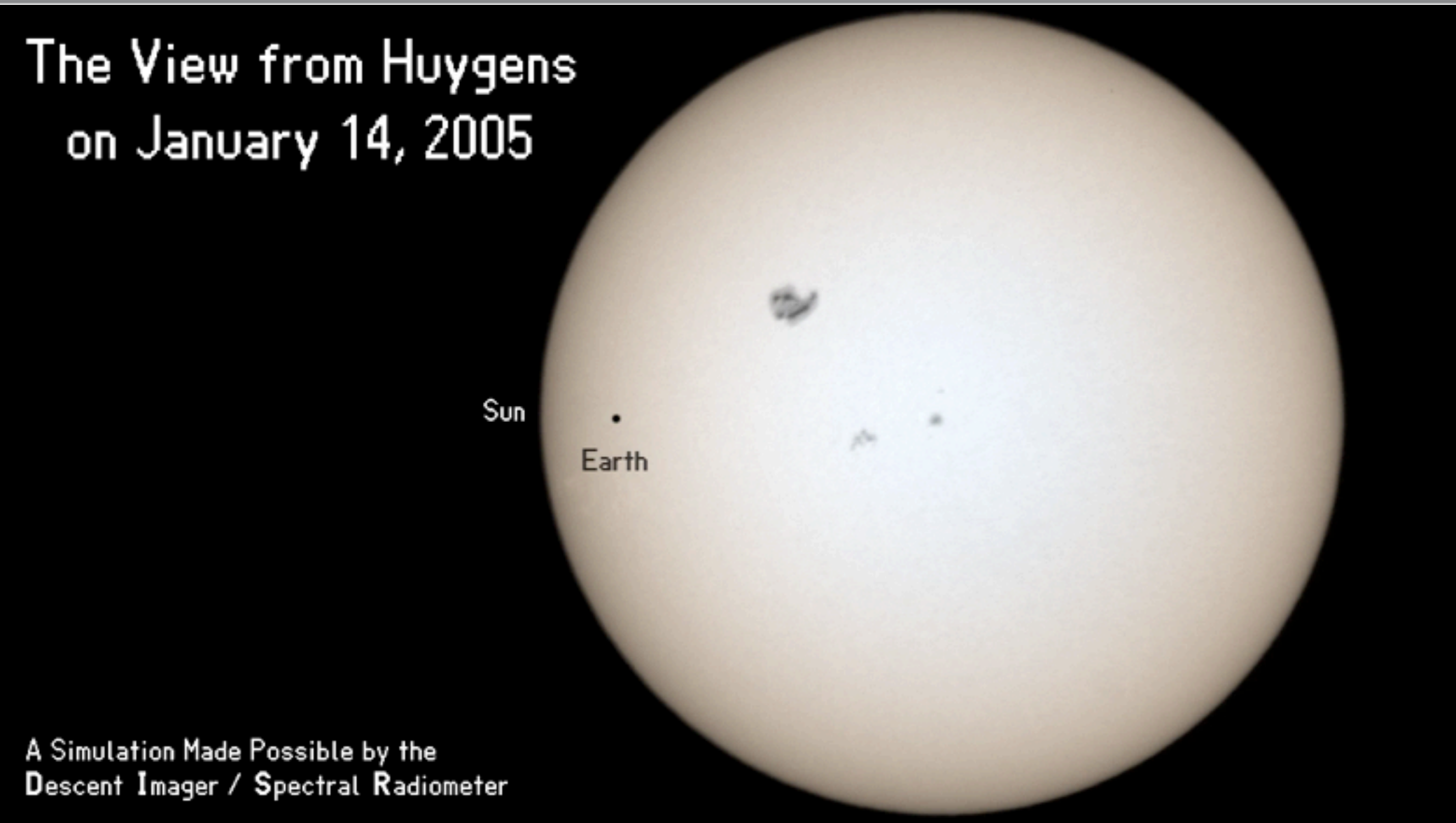

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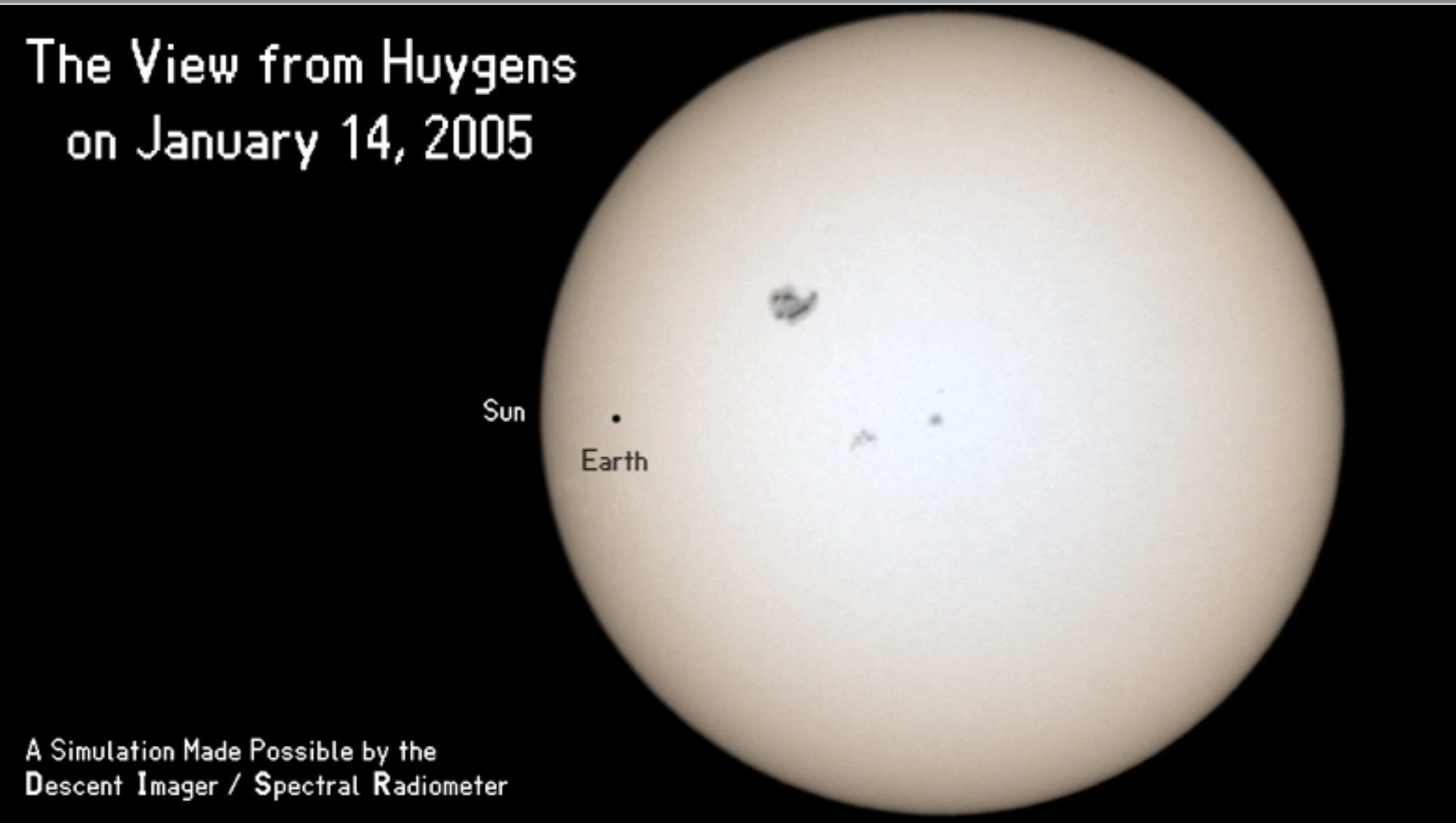


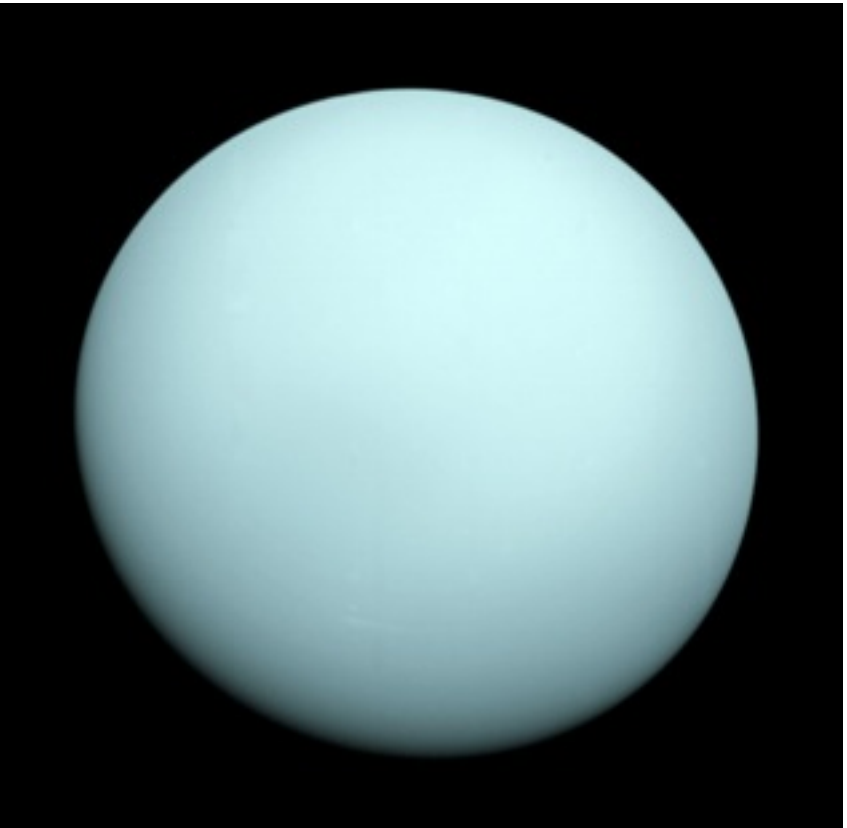
Future ideas for Saturn exploration

- Titan and Enceladus exploration, including Mogolfier balloon in Titan's atmosphere
- Aquatic lander in Titan's methane lakes
- Enceladus lander with ice mole
- Enceladus sample return

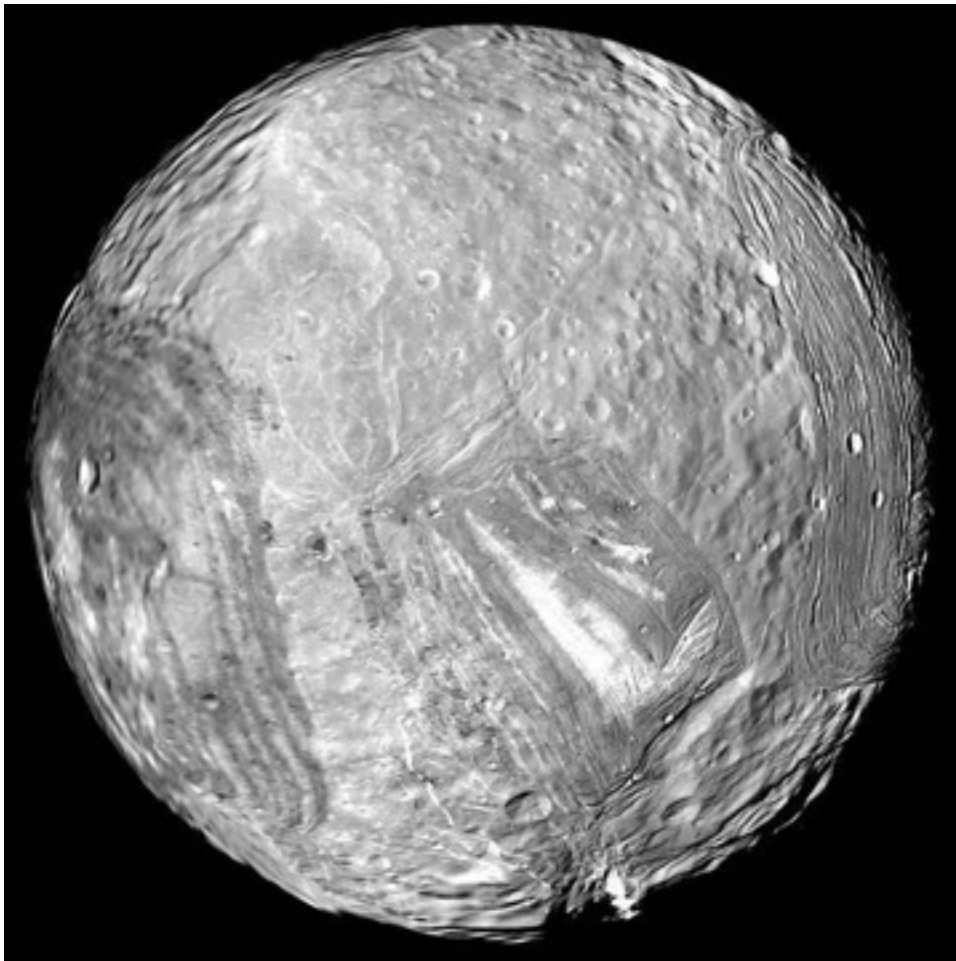
Exploration of Uranus and Neptune

- Voyager 2 flew by both planets and their moons (1986 Uranus, 1989 Neptune)

Uranus

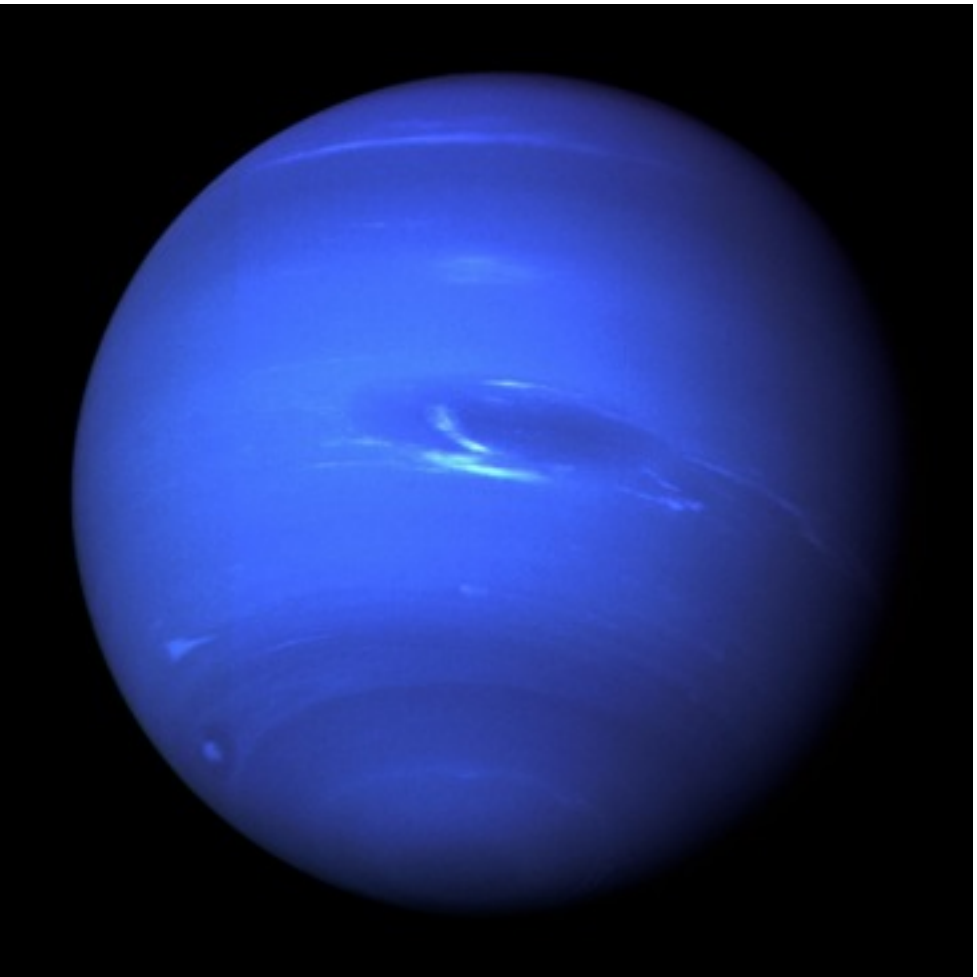


Miranda

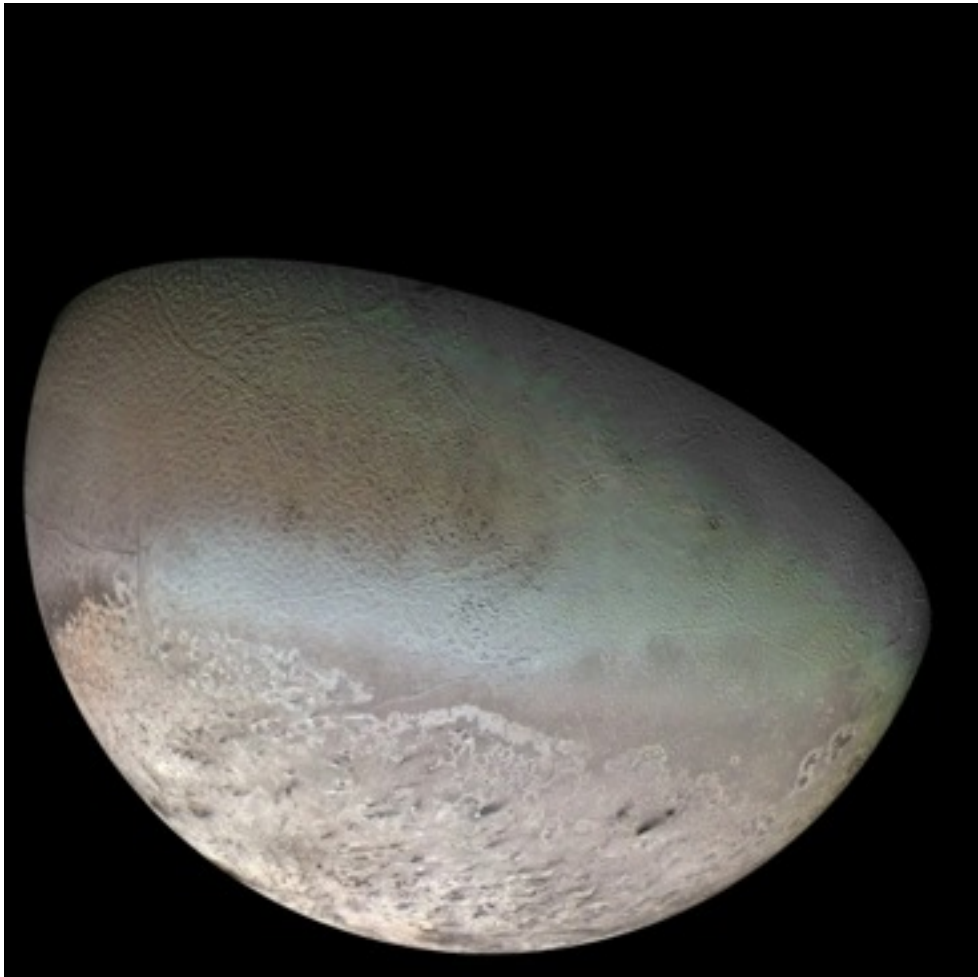


Voyager 2 at Neptune

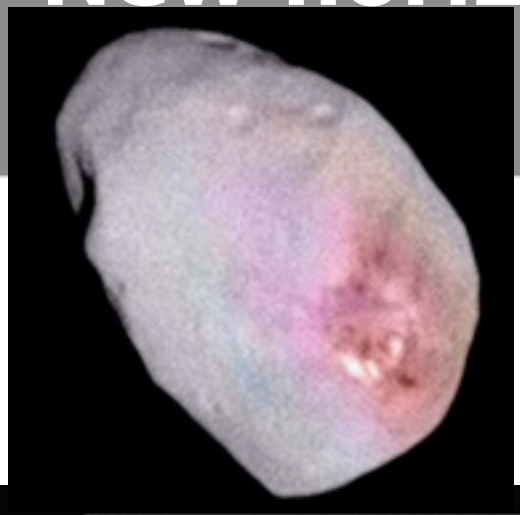
Neptune



Triton

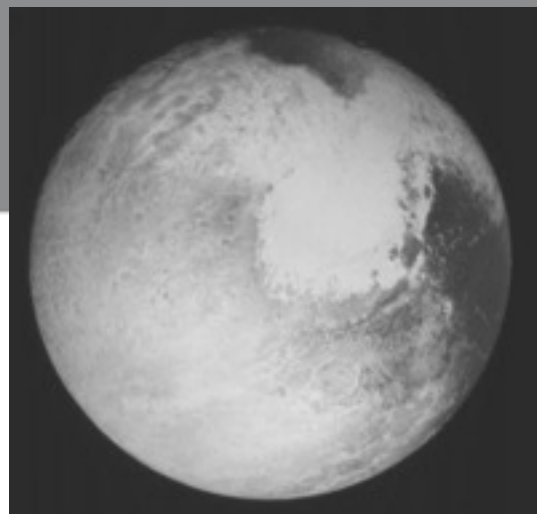


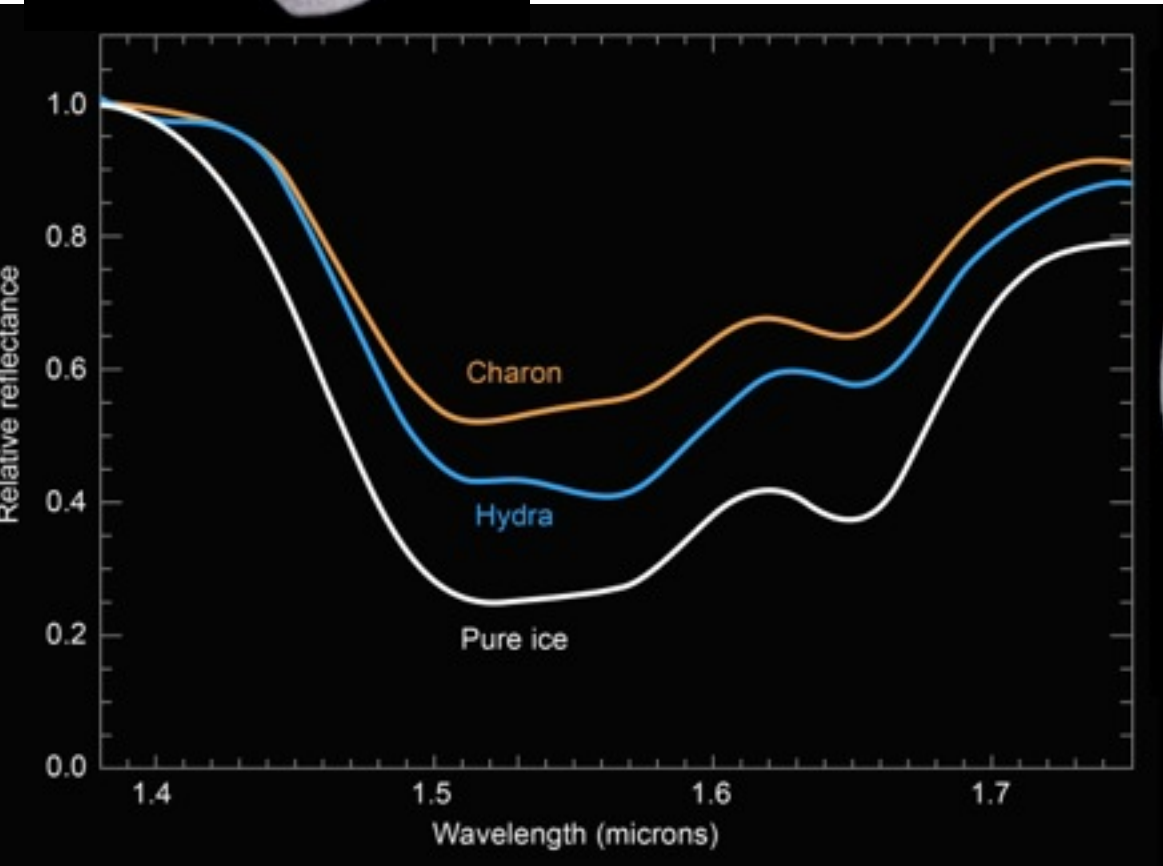
New horizons at Pluto (2015)

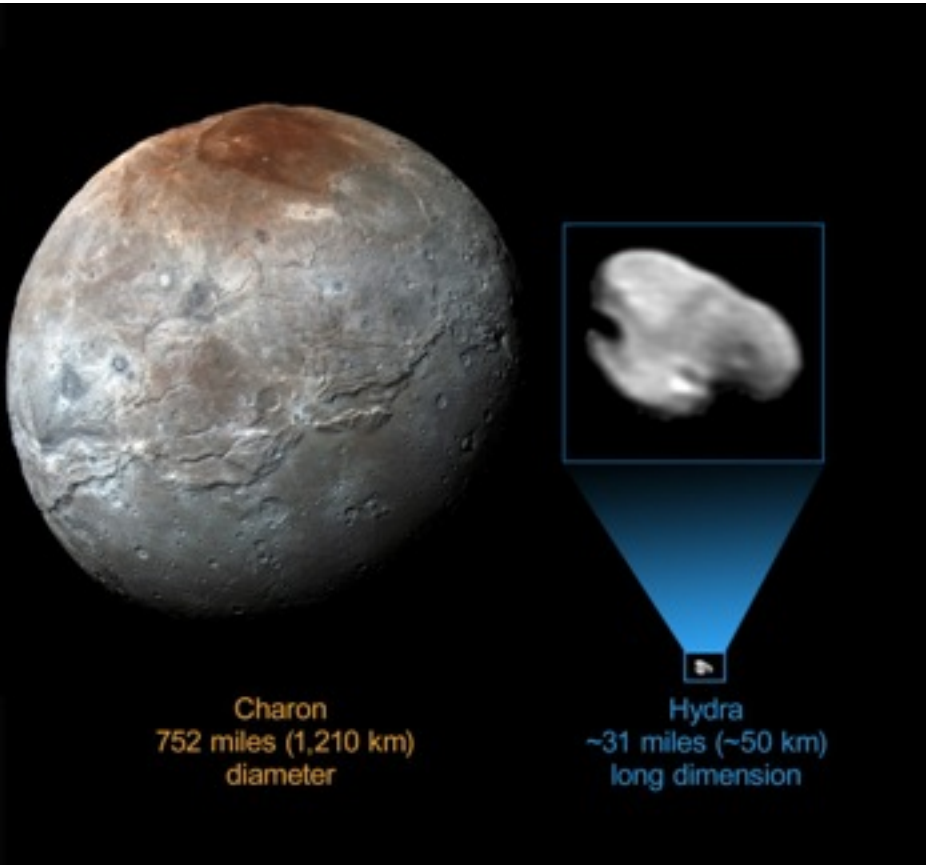


Nix

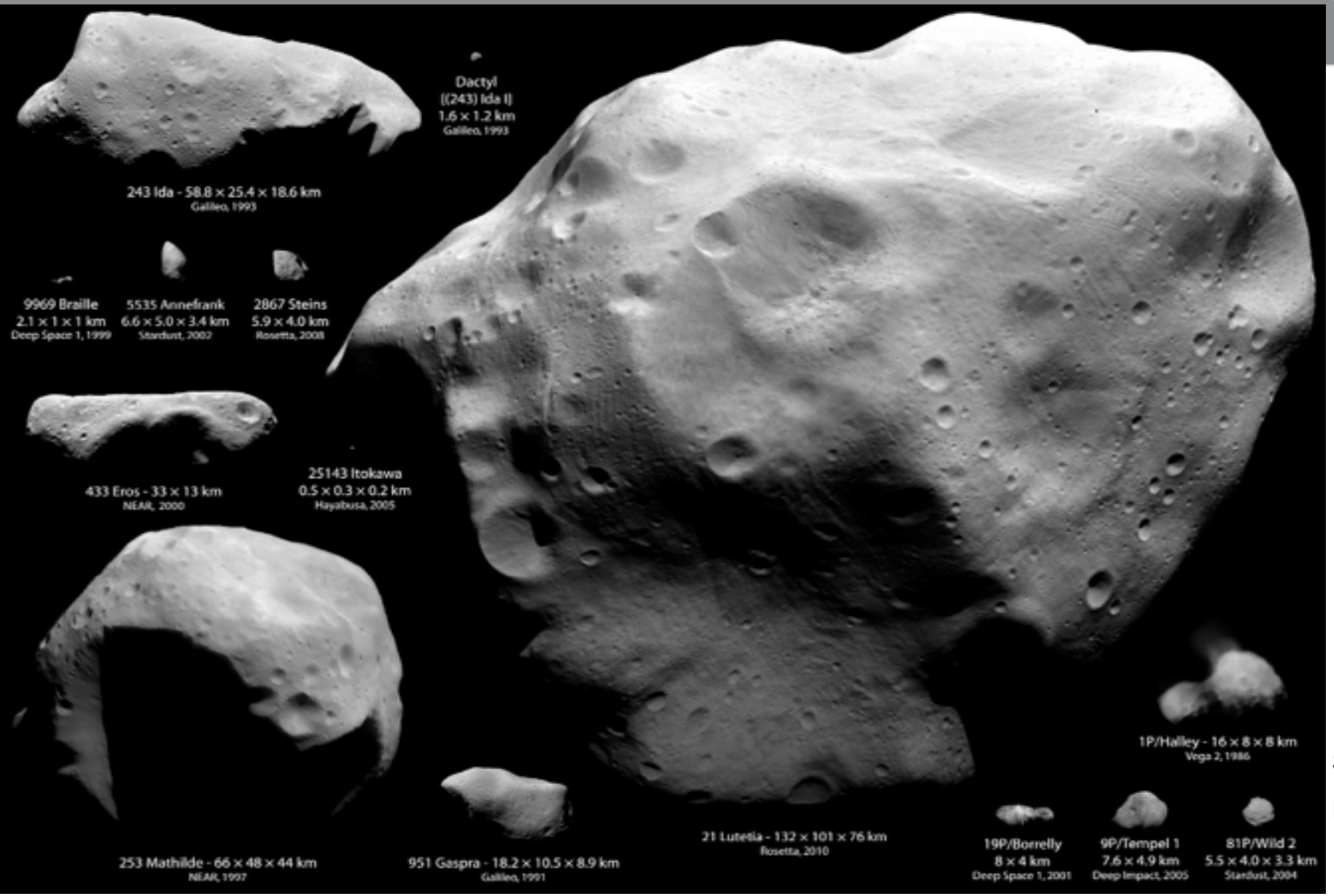
Pluto







Missions to small bodies: Overview



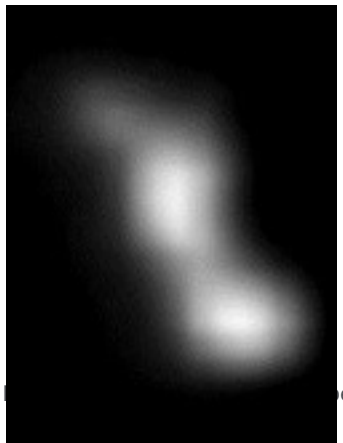
Source:

E. Lakdawalla

Missions to Asteroids: Flybys (I)

- Flybys allow a quick look on individual asteroids
  - Many of them are a secondary target that can be passed by on the way to the main mission target (e.g. Galileo, New Horizons, Rosetta)
  - Allows high resolution imaging and spectroscopy
  - Ten successful asteroid flybys so far, large variety in quality of output data

Braille (DS 1)



Masursky (Cassini)

AnneFrank (Stardust)

APL (New Horizons)

Source: Wikipedia

Missions to Asteroids: Flybys (II)

- First Asteroid flybys: Galileo on its way to Jupiter

Source: Granahan 2011, Icrarus

Gaspra: First asteroid observed from space (1991)

Source: NASA/JPL

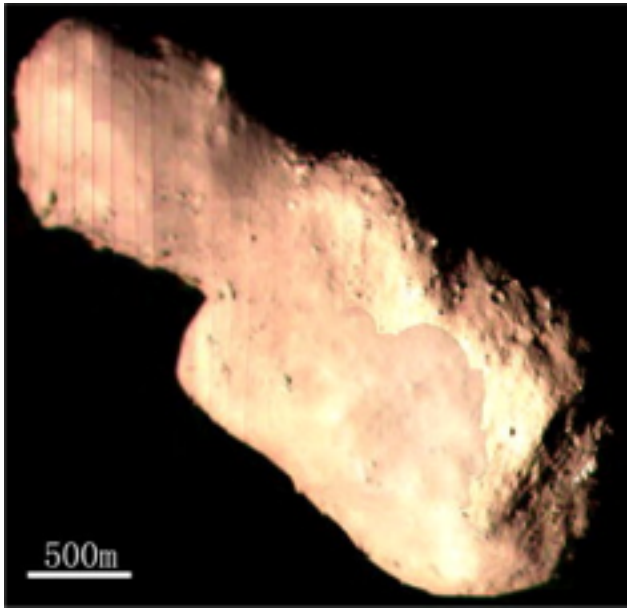
Ida and Dactyl: First asteroid satellite detected! (1993)

Missions to Asteroids: Flybys (III)

NEAR-Shoemaker flyby of Mathilde

Source:Wikipedia

Chang'e 2 flyby of Toutatis



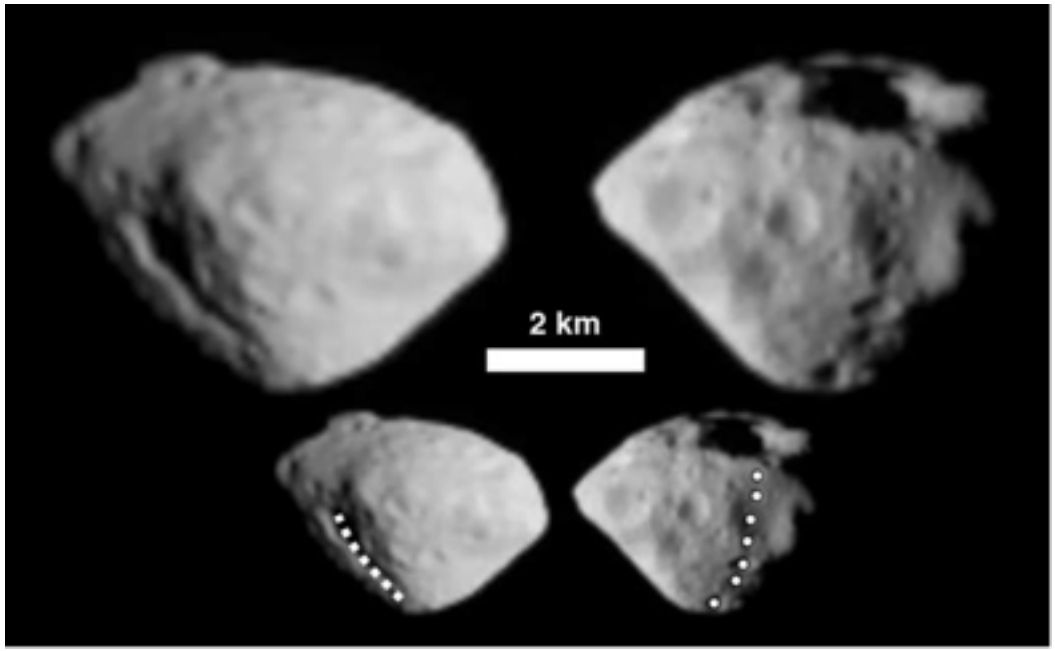
Source: Zou et al., Icarus 2014

Huge craters and low density: Impact in porous bodies causes compression, not destruction?

Missions to Asteroids: Flybys (IV)

Rosetta flybys en route to comet Churyumov- Gerasimenko

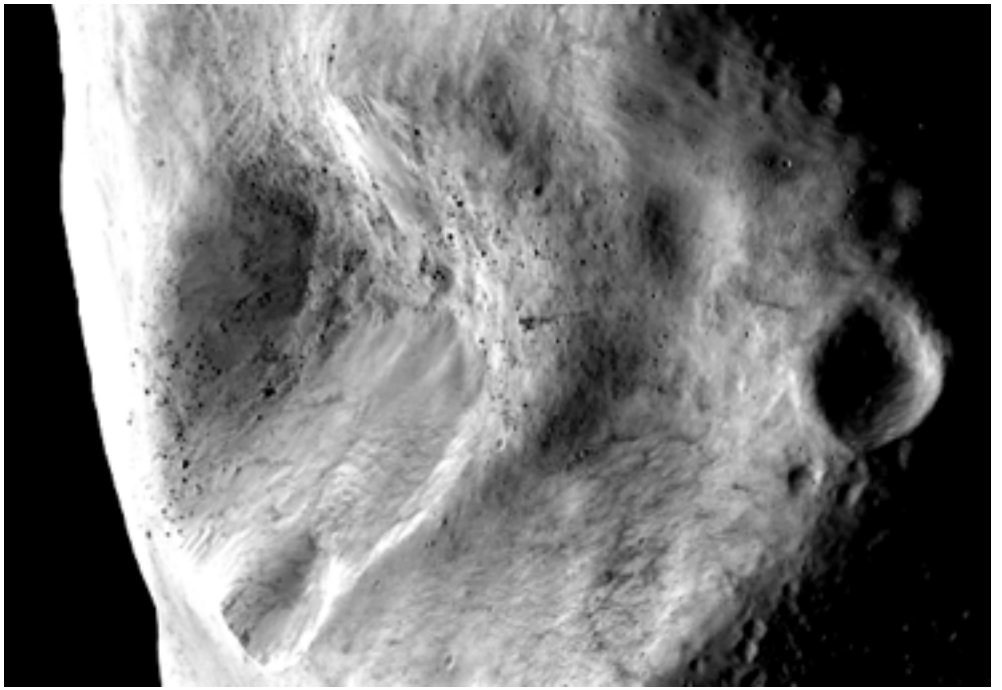
Asteroid Steins



Source: Keller et al. 2010, Science

First spacecraft observation of object shaped by fast rotation («YORP-Effect»)

Asteroid Lutetia



Credit: ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/ IAA/RSSD/INTA/UPM/DASP/IDA

Linear structures explained by waves from big impacts

Missions to Asteroids: Rendezvous I

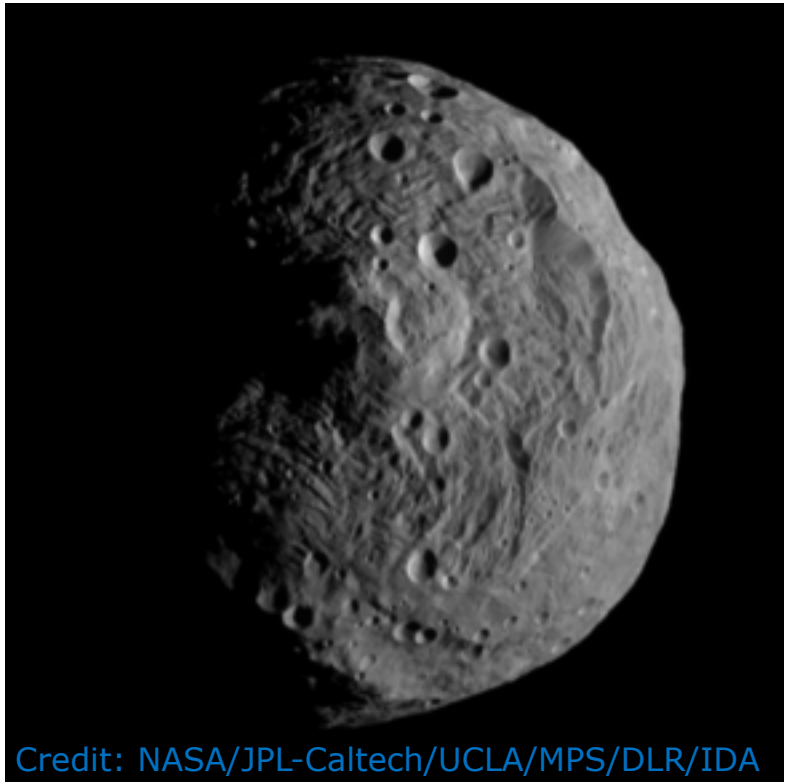
- NEAR-Shoemaker mission Rendezvous with asteroid Eros: First Asteroid Rendezvous
- Orbit insertion failed in 1999, than successful in 2000
  - NEAR stayed at its target for a year
- Mission ended with improvised landing
- First detailed explanation of regolith processes (e.g. boulder formation and destruction)

Source: Wikipedia

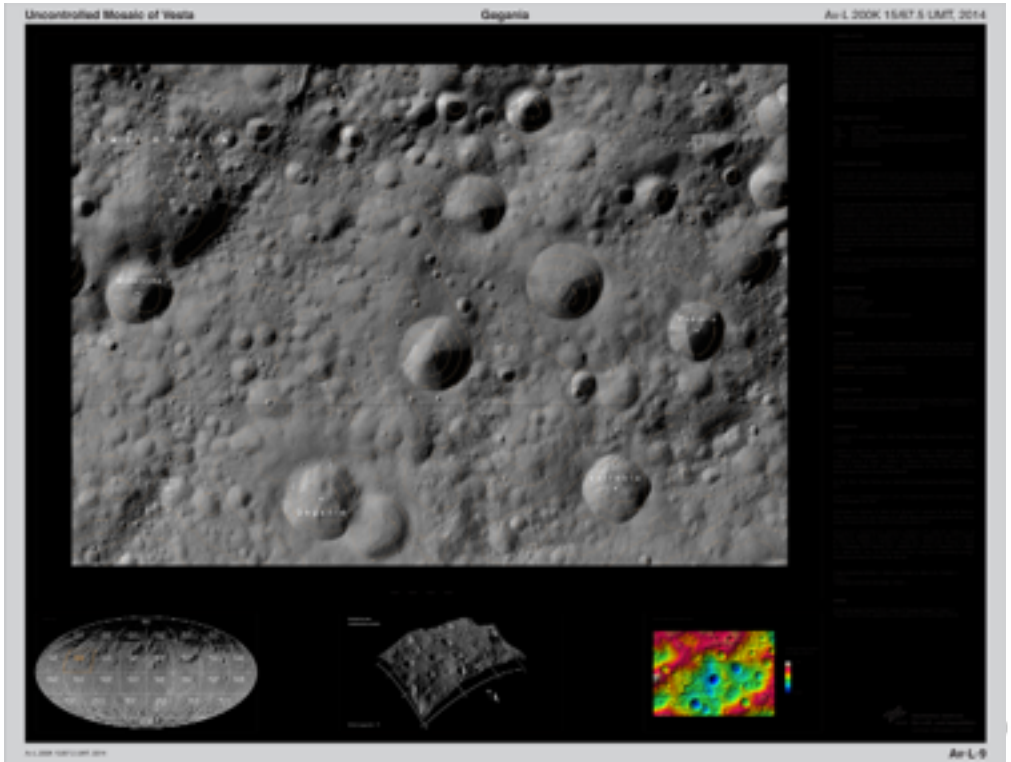
Source: NASA/APL

Missions to Asteroids: Rendezvous II

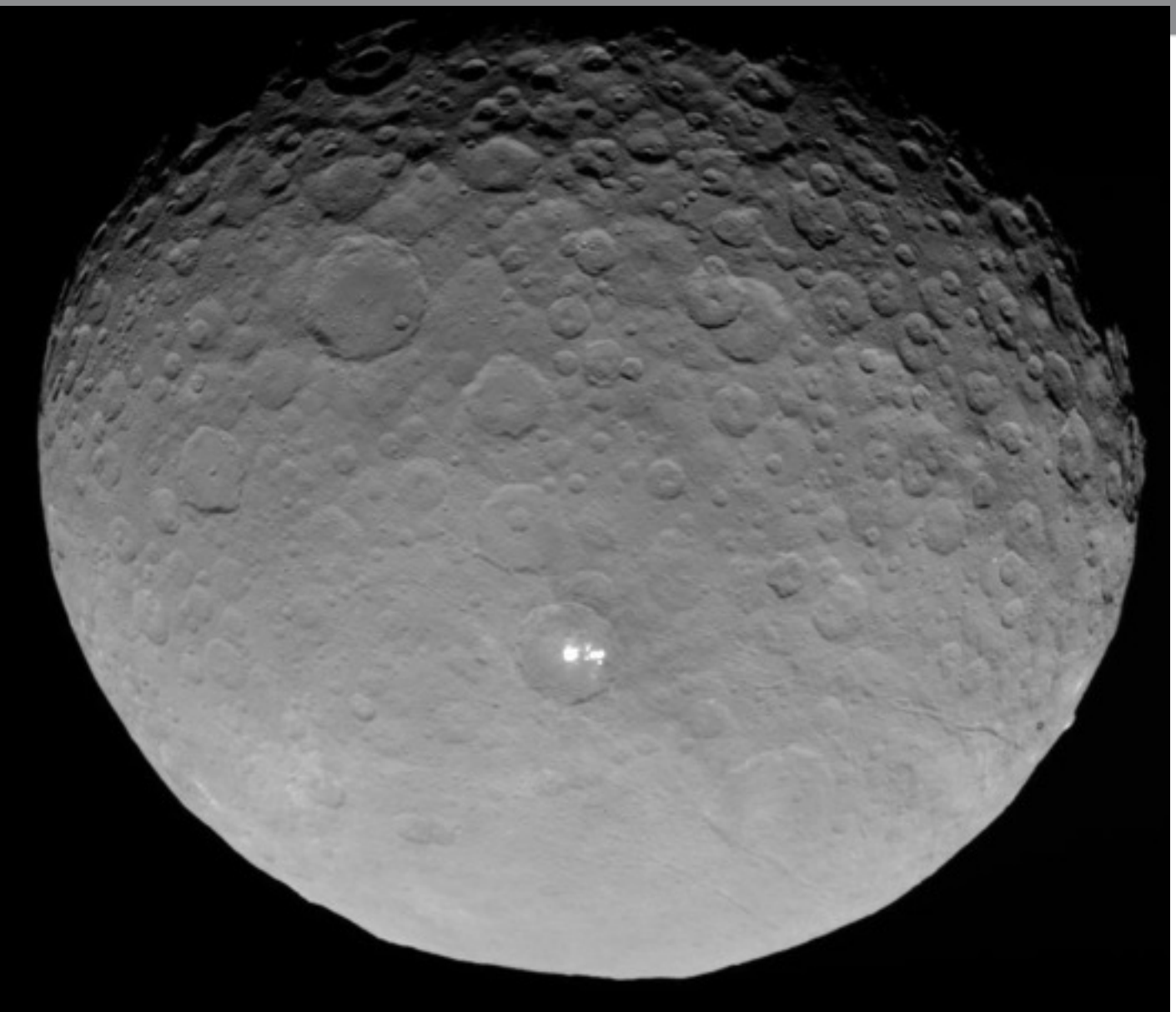
- DAWN mission to Vesta and Ceres
  - Visit of largest asteroids (Ceres is actually classified as dwarf planet)
  - Orbit around Vesta in 2011
  - Rendezvous with dwarf planet Ceres in 2015
  - Surface features on Vesta interpreted as transiently flowing water (perhaps)

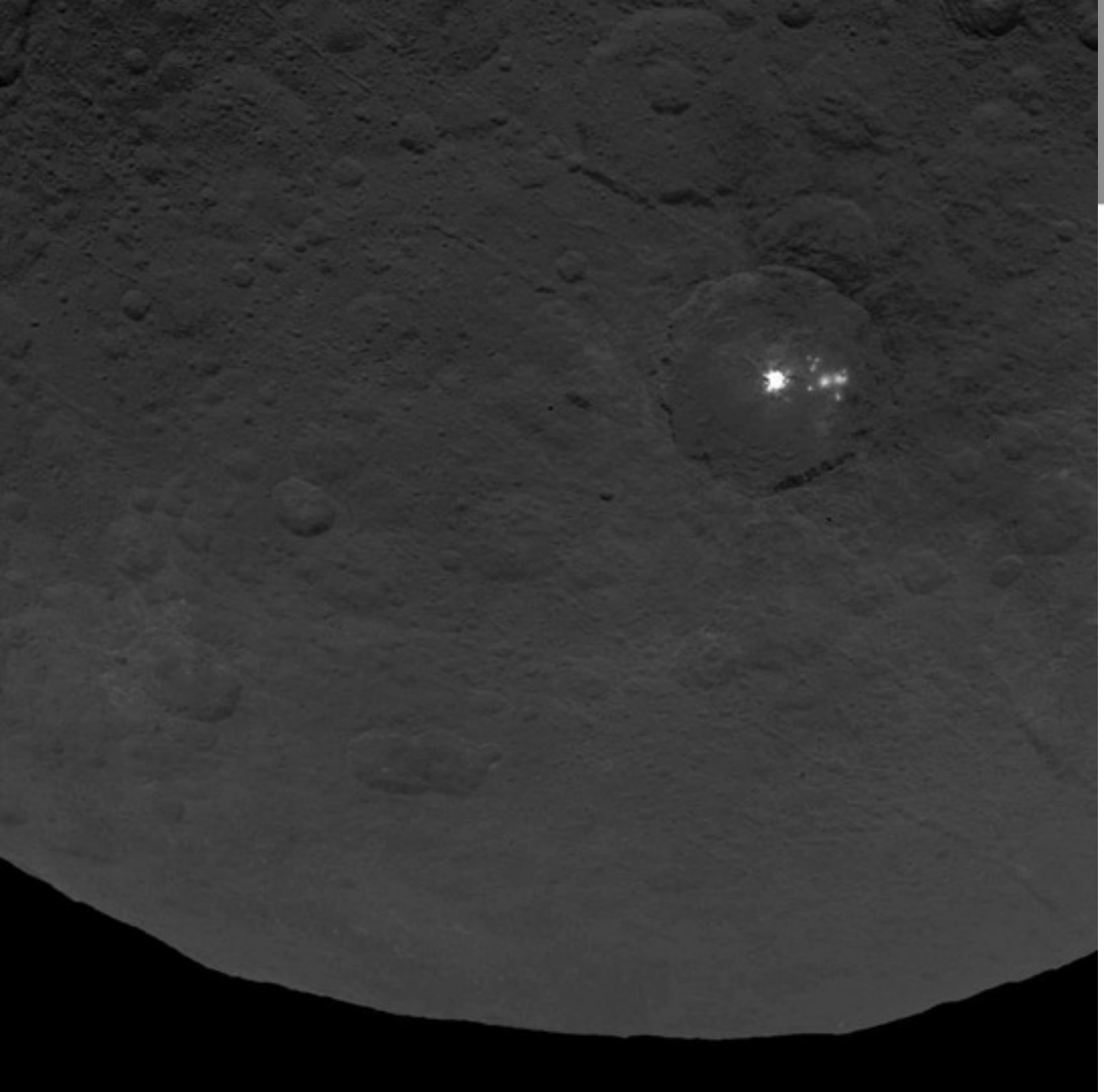


Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA



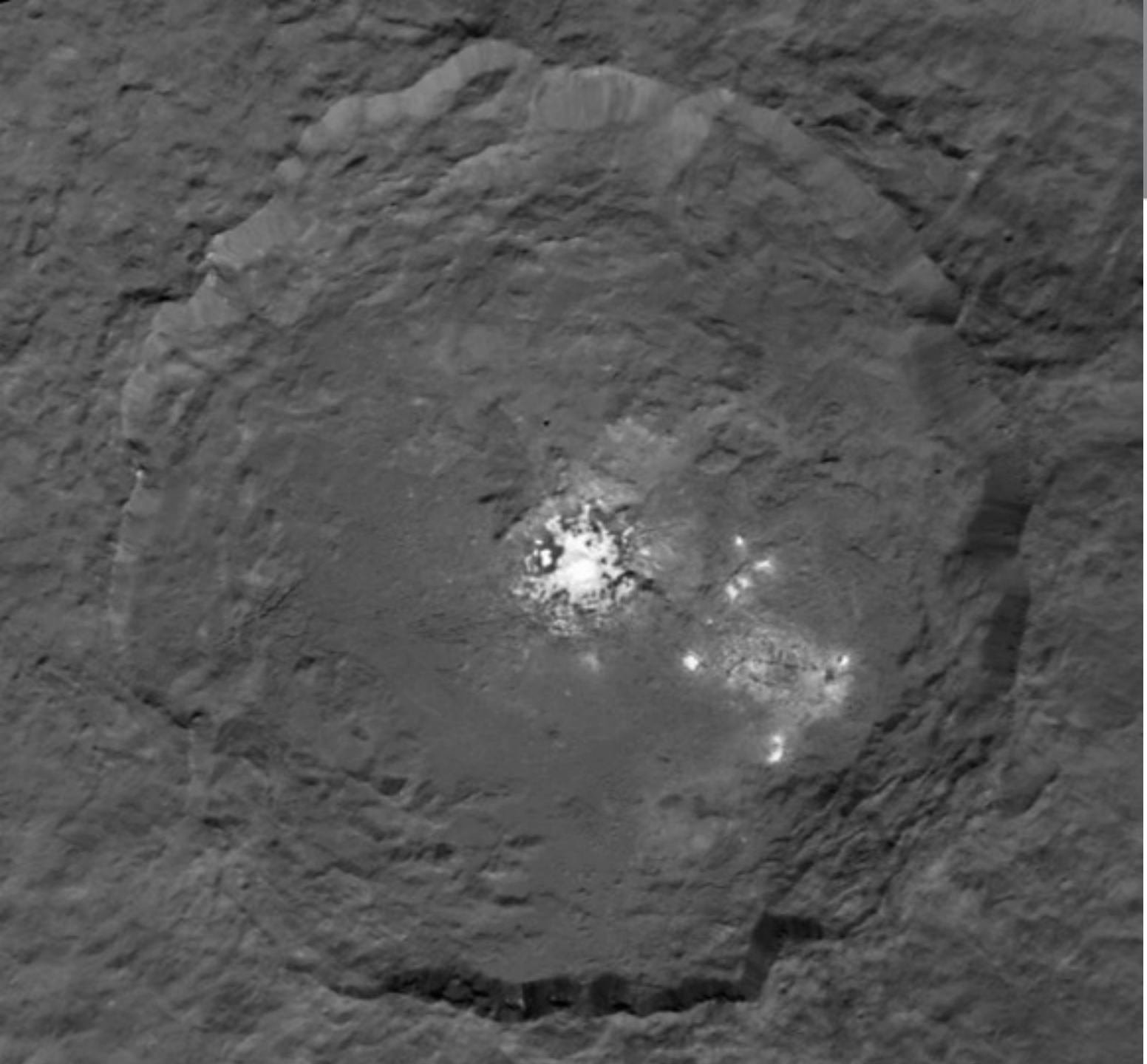
DAWN at Ceres





esa

European Space Agency



esa

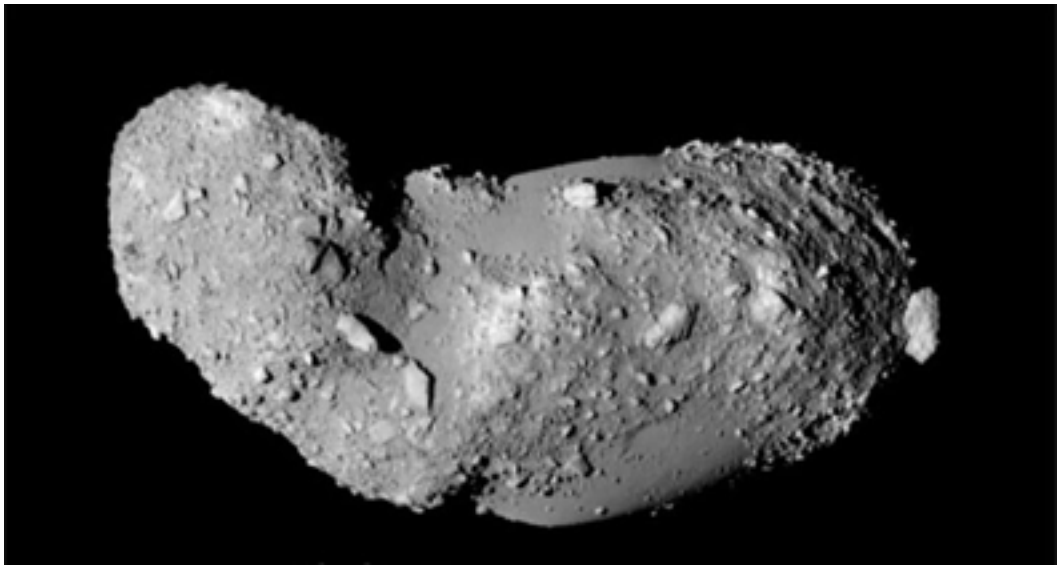
European Space Agency

esa

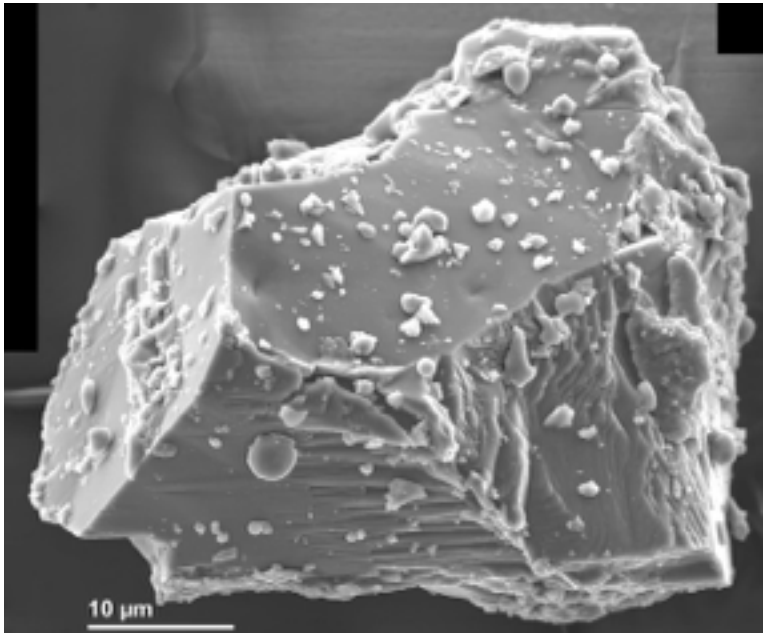
European Space Agency

Missions to asteroids: Sample return

- First sample return mission: Hayabusa to Asteroid Itokawa
- Launch in 2003, at Itokawa 2005-2006, return to Earth 2010
- Hayabusa fired a pellet into the asteroid surface and collected ~1500 dust grains (<300 µm, most <10 µm)
  - Firing most likely actually failed!
- Meteorite analog of asteroid confirmed, direct measurement of space weathering



Copyright: JAXA



Credit: Okayama University/JAXA

Missions to asteroids: Future sample return missions: Hayabusa 2

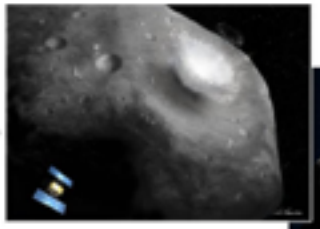
Hayabusa2 Mission Scenario

Launch
FY2014

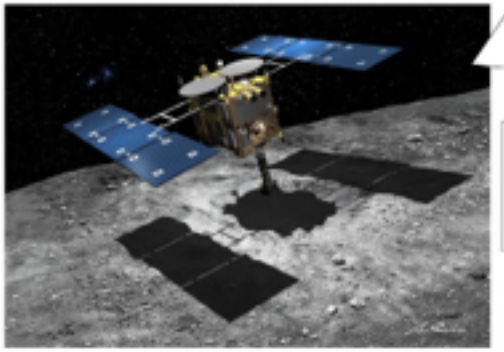
To Asteroid 1999 JU3

Asteroid Arrival
June 2018

Hayabusa2 observes the asteroid by the optical camera, the near infrared spectrometer, Laser altimeter, etc. Then it approaches near the surface of the asteroid, releases small rovers (MINERVA2) and a small lander (MASCOT), and tries to get the surface material.



The impactor will collide to the surface of the asteroid to create an artificial crater. The crater will be observed to study underground matter.



Spacecraft will go some other places such as Lagrange point.

Asteroid Departure
December 2019

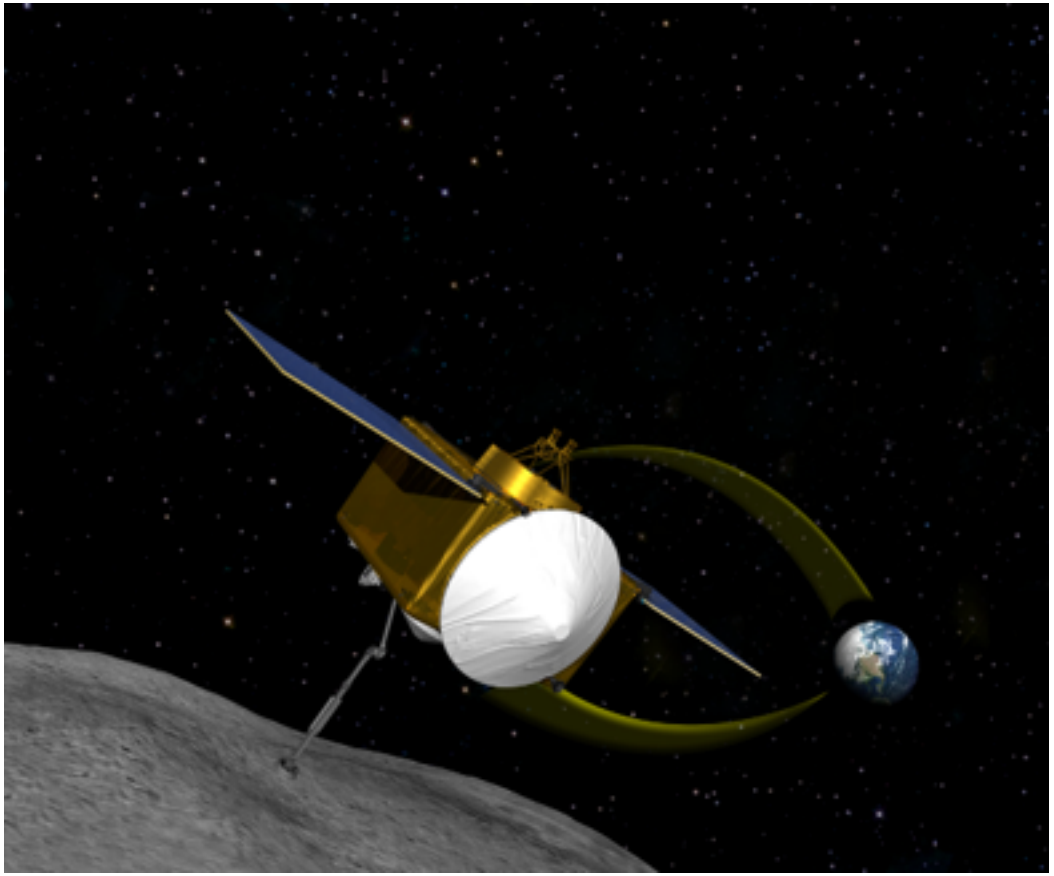
Earth Return
December 2020

Sample Analysis

After confirming the safety, touchdown will be performed to get the subsurface matters.

Missions to asteroids: Future sample return missions: OSIRIS-Rex

- Launch 2016, return 2023
- Sampling with an robotic arm, up to 2 kg of material

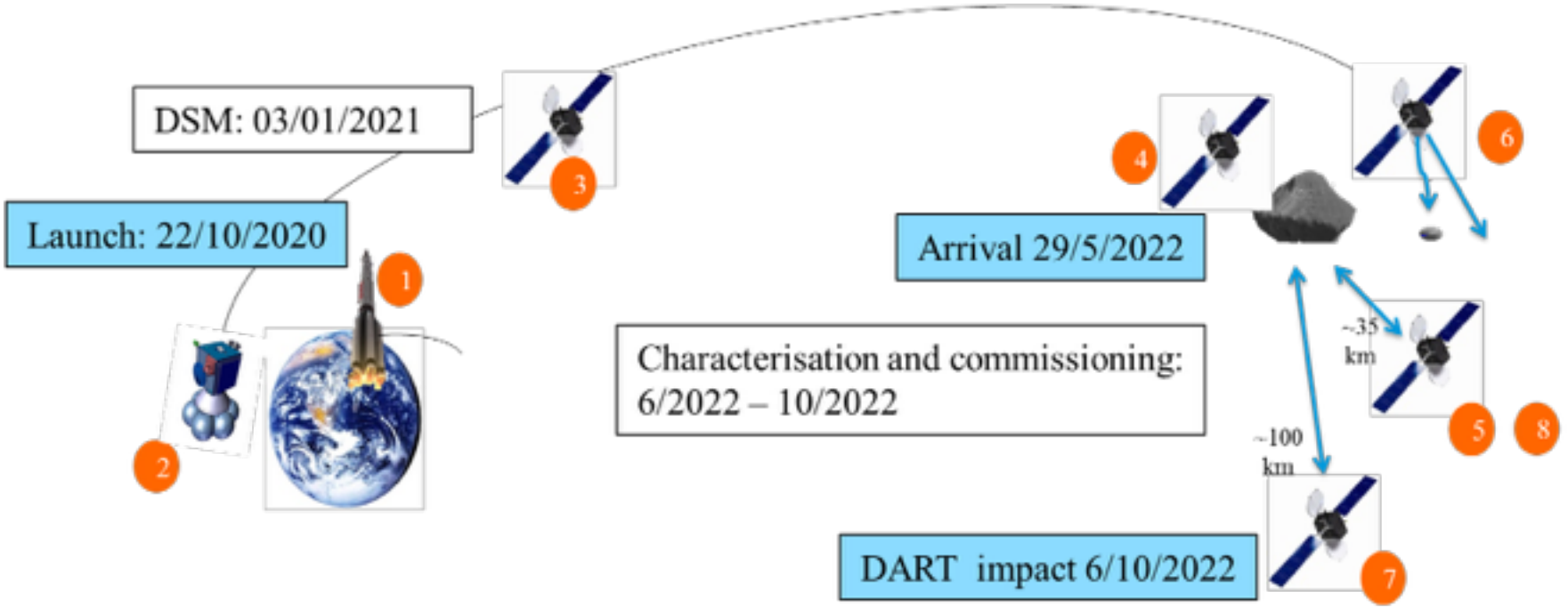


Missions to Asteroids: Asteroid mining?

- Idea of asteroid mining became popular with «Planetary Resources» project
  - Idea is to return precious elements that are rare on Earth
- Economic feasibility?
  - See price per kg of sample return missions

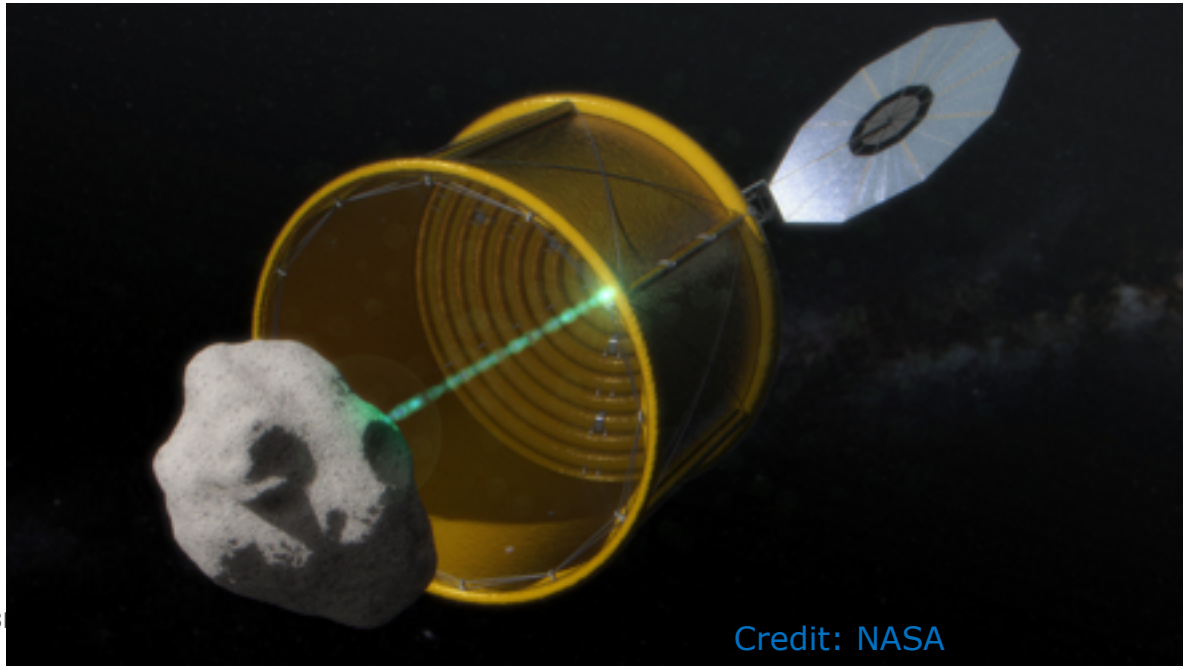
Missions to Asteroids: Asteroid deflection

- Idea: Impact an asteroid to deflect it from collision coarse with Earth
- AIM concept: Demonstrate feasibility by changing the orbital period of an asteroid moon



Missions to asteroids: Manned missions

- Asteroid Redirect Mission
  1. Find a small (few meters) Asteroid
  2. Capture it in a capture device and transport it in an orbit around the moon
  3. Have it explored and sampled by Astronauts
- This mission is studied by NASA!



Credit: NASA

Comet missions

- First comet missions were the “Halley armada” in 1986
  - ESA, Russian, and Japanese spacecraft flew by comet Halley
- Further flybys over the years
  - Deep Space 1 at Borelly (2001)
  - Stardust at Wild 2 (Comet coma sample return)
  - Deep Impact (extended mission) at Hartley 2 in 2010
- Flyby + Impact by Deep Impact in 2005 (Comet Tempel 1)
- Current: Rosetta
  - First comet Rendezvous and landing

Cometary nuclei flown by by spacecraft before Rosetta

Overall, all look different: Different formation or different evolution?

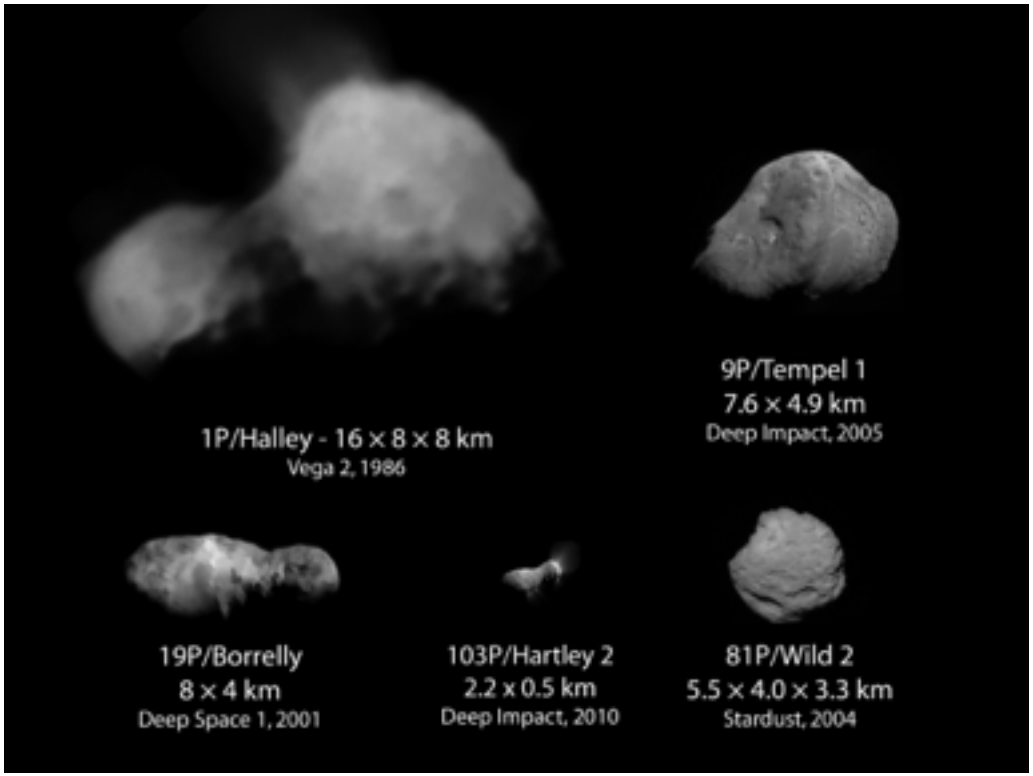


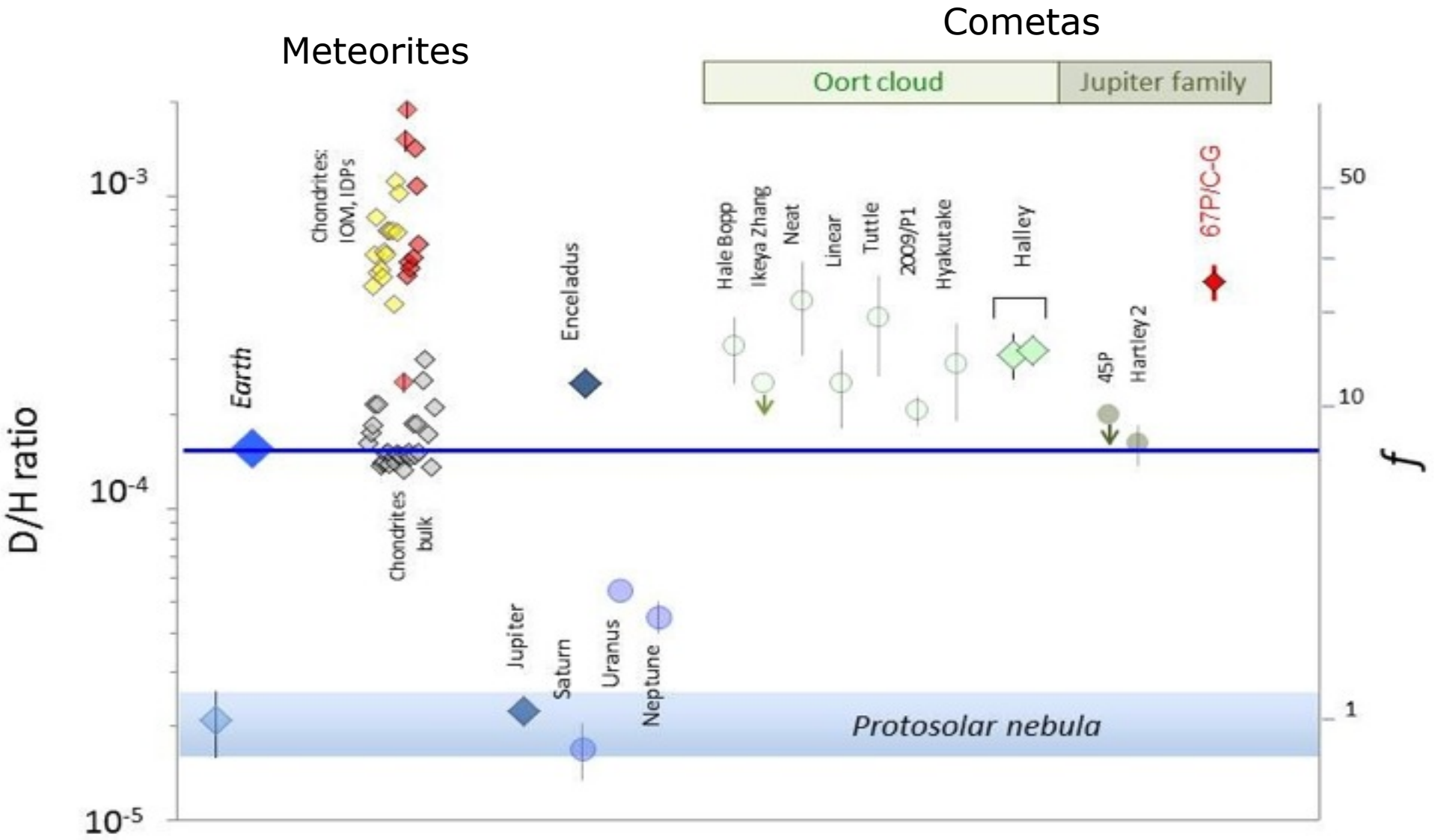
Image credit: L. Elenin

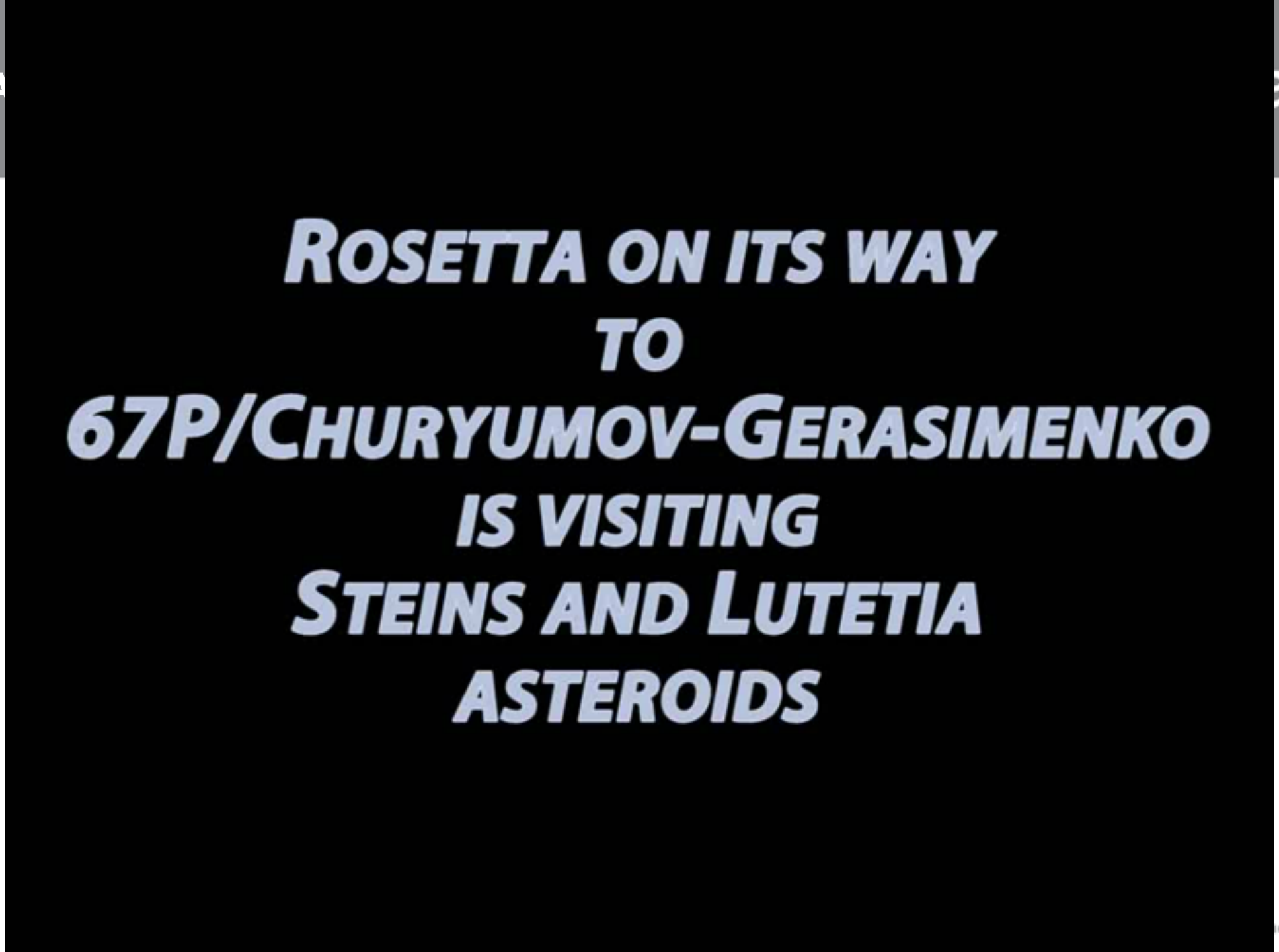
1P/Halley: Highly active, low albedo, relatively little geological information about the surface
19P/Borrelly: Diverse geology, different types of terrain, no ice found on surface!
81P/Wild: Rugged terrain, impact craters ?
9P/Tempel 1: Diverse terrain, primordial layers found?, impact craters ?, very little ice found on surface
103P/Hartley 2: Hyperactive, diverse terrain, extreme shape, ice blocks (cm-dm sized) emitted from nucleus

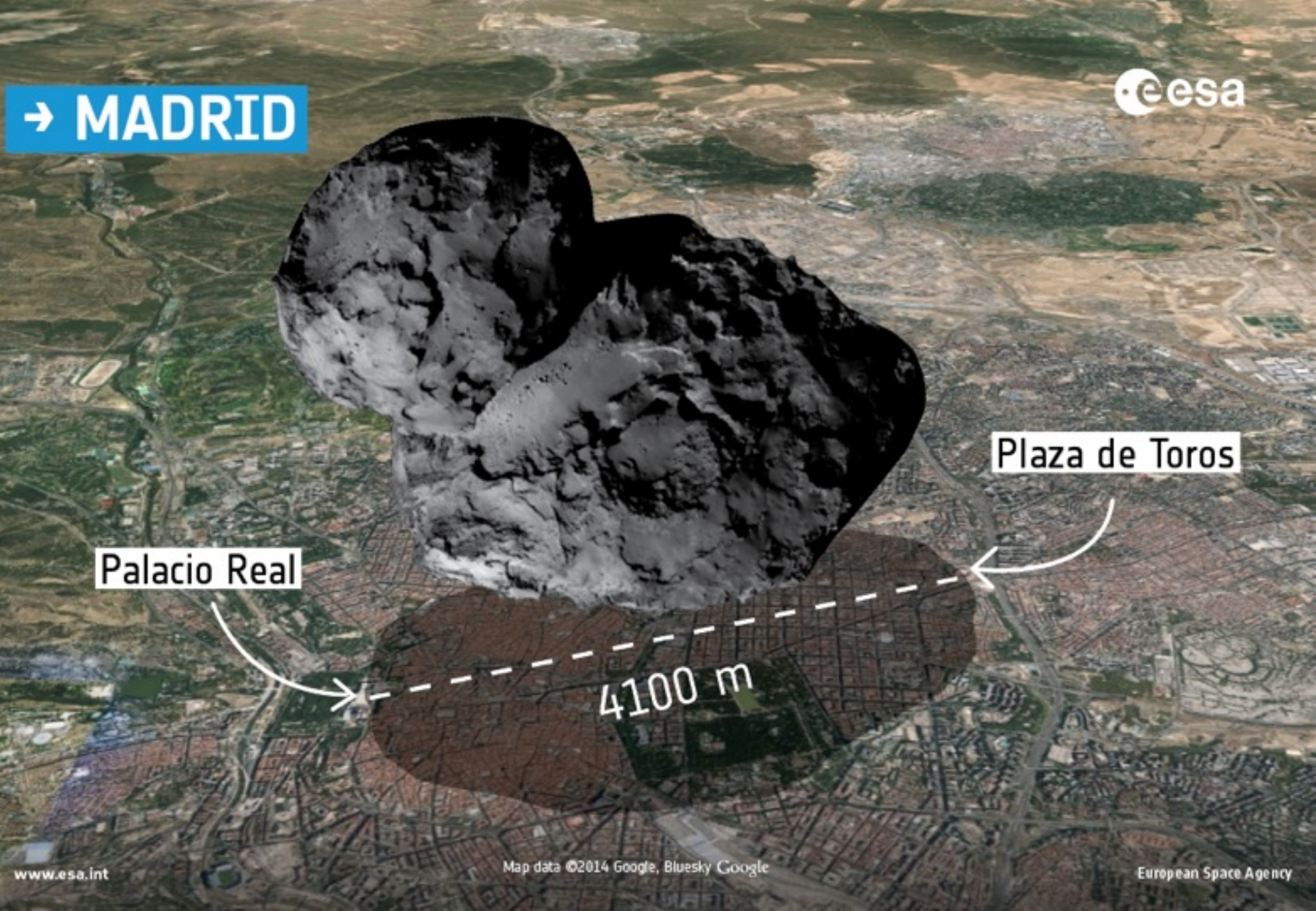
Rosetta mission to comet 67P/Churyumov Gerasimenko

- Monitoring of the activity of a comet through its perihelion passage
- Ground truth from landing
- Some Results:
  - Comets formed in the protoplanetary disk!
  - D/H in comet 67P different from Earth

D/H en el sistema solar (observaciones)




ROSETTA ON ITS WAY
TO
67P/CHURYUMOV-GERASIMENKO
IS VISITING
STEINS AND LUTETIA
ASTEROIDS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European Space Agency

Amazing view of comet C/G

Landing on a comet

Landing on a comet

Landing on a comet

Conclusions

- Robotic space missions have changed the planets and some small bodies from astronomical objects to geological objects
- The solar system provides ground truth for the investigation of planetary systems and search for life around other stars