1. Taking Stock

Topic 1a: Rocky planets

Mercury

Venus

Earth

Moon

Mars

Topic 1b: Gas giants and beyond

Jupiter

The satellites of Jupiter

Saturn

The satellites of Saturn

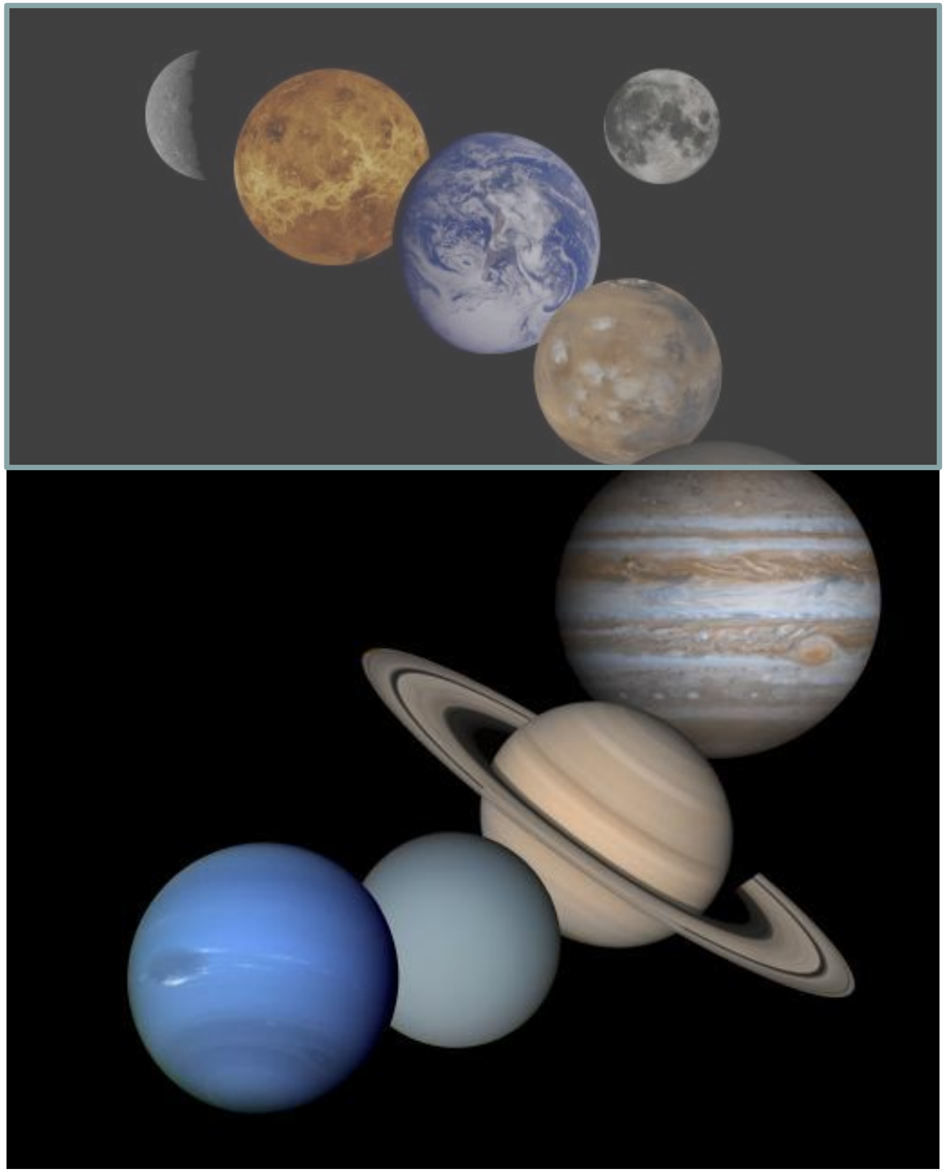
Uranus

Dwarf planets

Beyond the Kuiper Belt

The Solar System

Not examinable



© NASA

Large – Mostly rocks and gas

Sun 1,390,000 km diameter

Mercury 4,879 km

Venus 12,104 km

Earth 12,756 km
+ Moon 3,475 km
146 million km from Sun (1 AU)

Mars 6,794 km

Jupiter 142,984 km

Saturn 120,536 km

Uranus 51,118 km

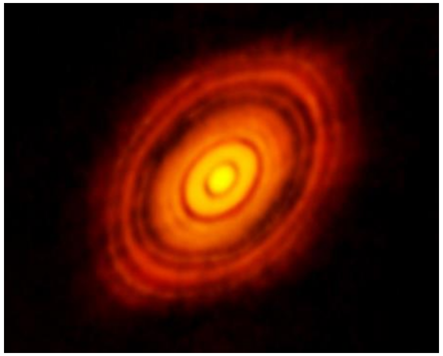
Neptune 49,528 km
4.5 billion km from Sun (30.07 AU)

… and Pluto …

The planetary snow line

Definition

The frost line, also known as the **snow line** or **ice line**, is the distance from a star where it is cold enough for volatile compounds to condense into ice grains.



Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF).

Its radial position wiill change with the element (H_20, NH_3, CH_4, $C0_2$, CO …)
(due to their respective condensation temperatures)
with the partial pressure into the planetary nebula
with time (as the nebula evolves into a full planetary system)

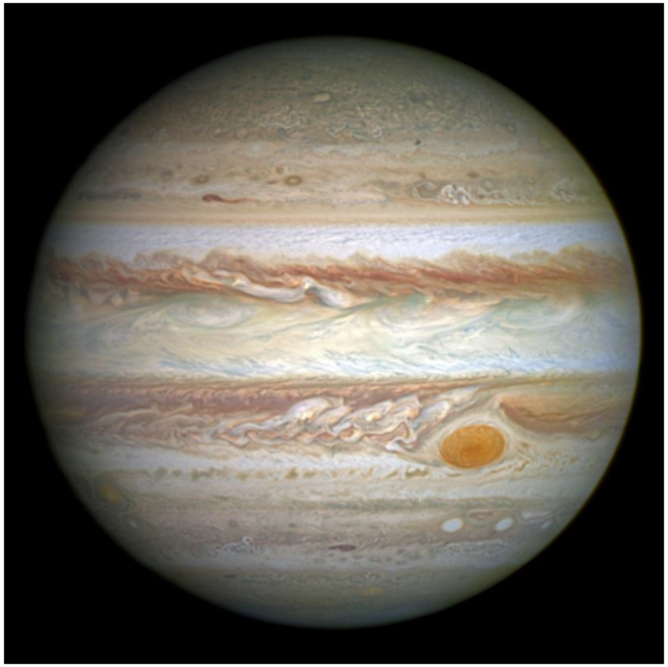
For our Solar System: it is now ≅ 5 AU. It separates rocky planets from gas giants.

The asteroid belt, between Mars and Jupiter, suggests that the water snow line during formation of the Solar System was located close:

The outer asteroids are icy objects
The inner asteroid belt is largely devoid of water.

This implies that, when planetesimal formation occurred, the snow line was at ≅ 2.7 AU.

Jupiter



11 times larger than Earth – 5.2 A.U. from Sun

Orbits the Sun in 4,333 days

1 Jupiter day = 9.9 hours

Atmosphere: mostly H_2, He (like Sun …)

Upper clouds: Ammonia, H_2O, …

"Great Red Spot" and huge storms

Gas giant

As *P* and *T* increase, H_2 becomes liquid

Deeper: H_2 might behave like metal

Does it generate the huge magnetic field?

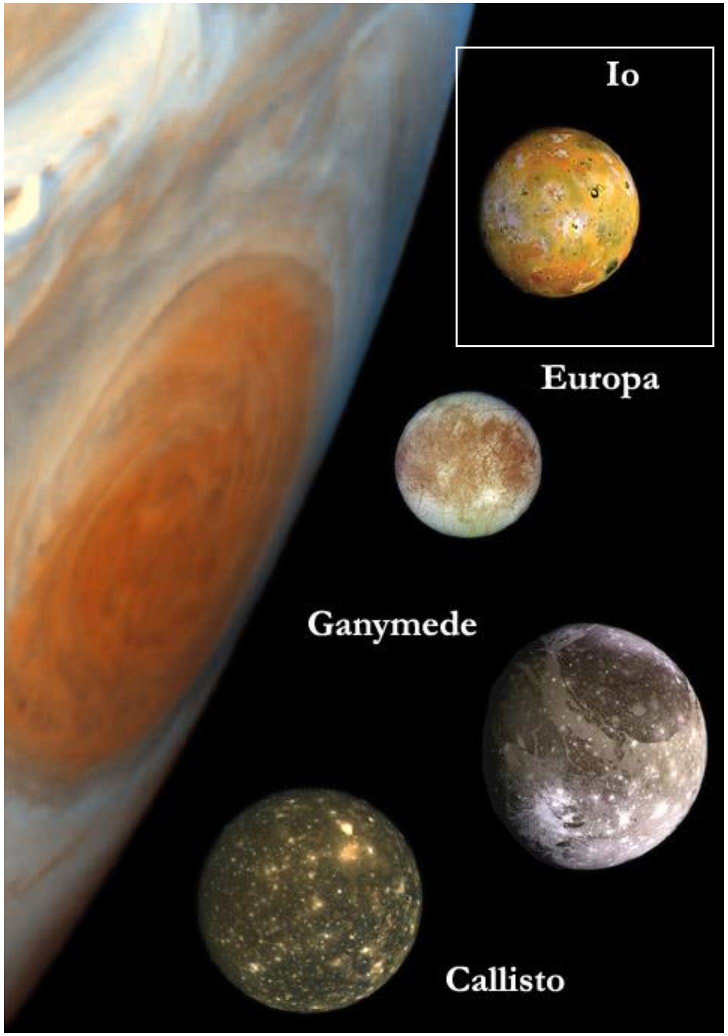
Magnetosphere: 7 - 21 times the diameter of Jupiter, 16 – 54 times B_{Earth}

Missions: Cassini (2004 – 2017) – NASA Juno (2016)

Open questions:

- Water proportions in atmosphere: links to planet formation theory
- Composition, temperature, cloud motions deep into atmosphere
- Exact magnetic and gravity fields (planet's deep structure)
- Magnetosphere near the poles, especially the auroras

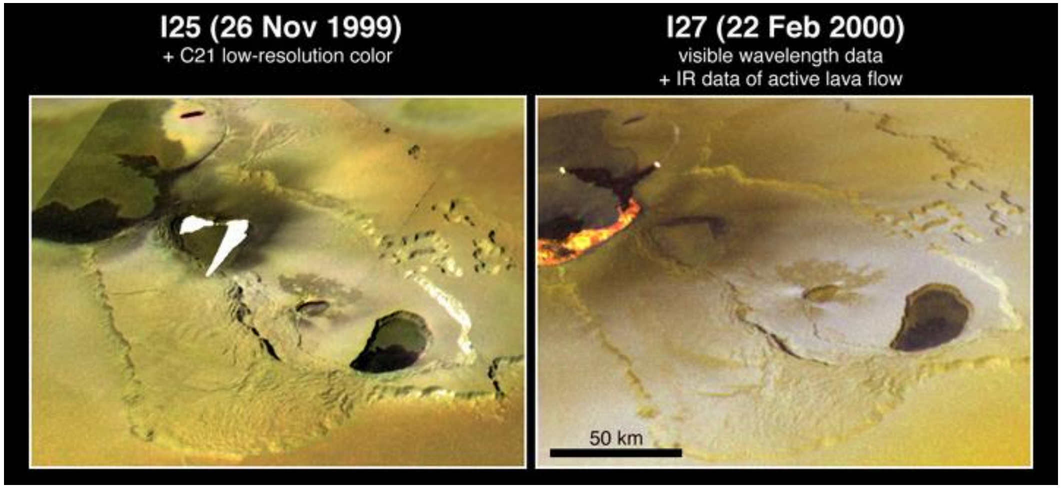
The Moons of Jupiter



© NASA

huge volcanoes

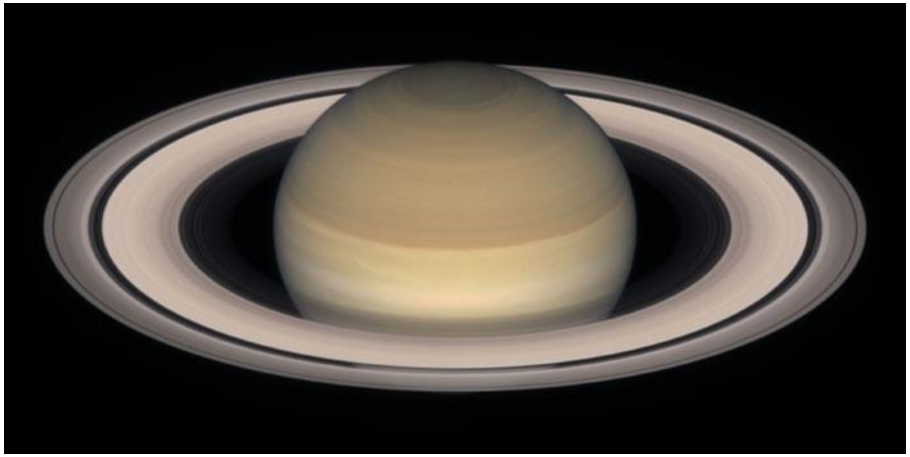
eruptions
330 km high



© NASA

53 satellites (+ 16 unconfirmed) – Some are within Jupiter's magnetosphere

Saturn



9 times larger than Earth – 9.5 A.U. from Sun
(plus the rings)

Orbits the Sun in 29 years
1 Saturn day = 10.7 hours?

Atmosphere: mostly H_2, He (like Jupiter)
Huge winds (> 500 m/s)

Gas giant
dense metal core (Fe, Ni)
enveloped by liquid metallic H_2

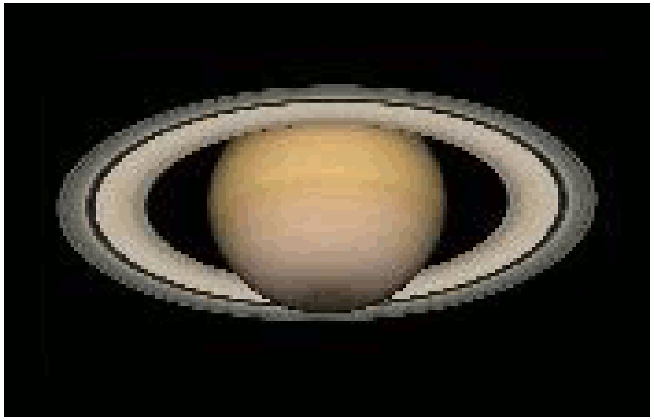
Magnetosphere: very large (20 times Saturn's diameter)
Large ring system: nearly invisible from Earth every 29.5 years

Key mission: Cassini (2004 – 2017)

Open questions:

- Atmosphere composition and structure at depth
- Evolution of the rings

Saturn and its rings



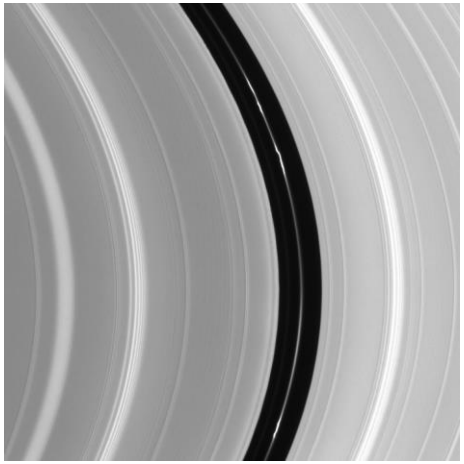
Wikipedia - CC BY-SA 4.0

Orientation as seen from Earth varies over 1 Saturn year (29 Earth years)

Extends 7,000 km to 80,000 km

Estimated local thickness: <10 m – 1 km

99.9% pure water ice with impurities
Mainly particles 1 cm – 10 m in size



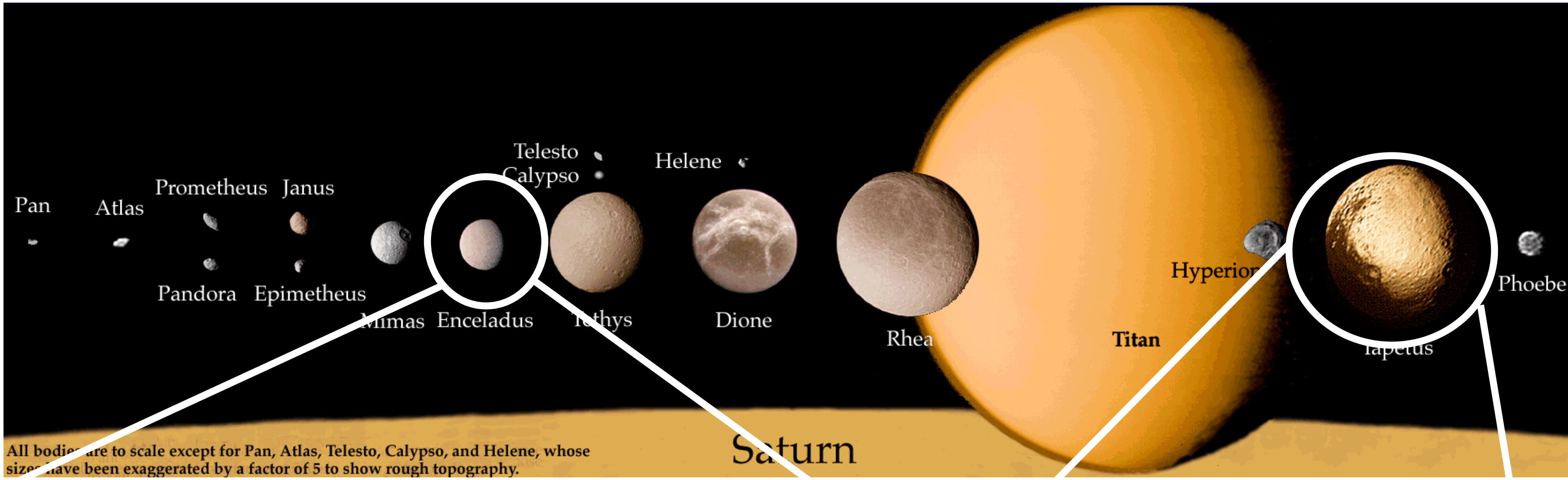
NASA/JPL/Space Science Institute

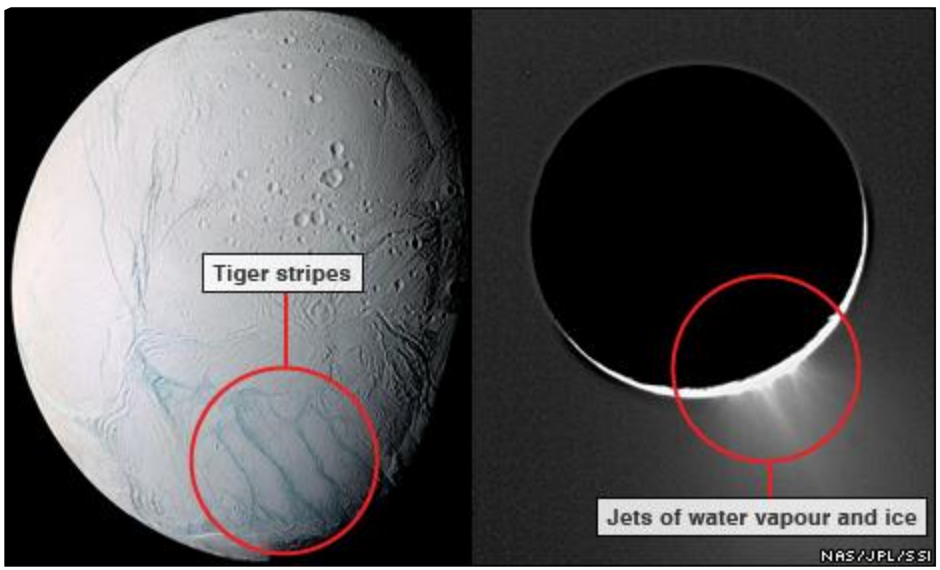
Ring origins: several theories
Some rings are fed by cryovolcanic eruptions from satellites like Enceladus

Gaps in rings created by orbiting moonlets

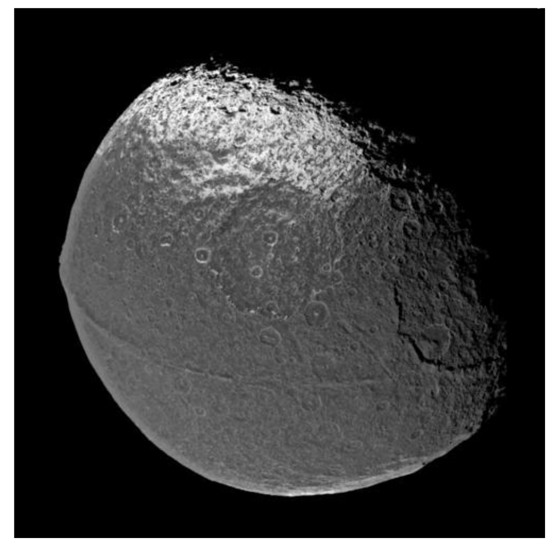
Latest models estimate they are relatively recent (100M years?)

Saturn and its Satellites



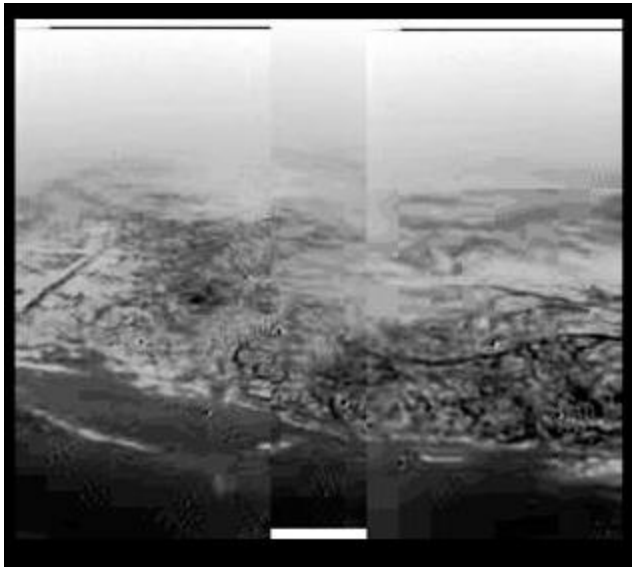


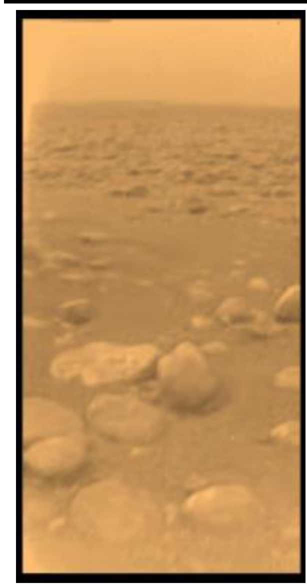
Cassini plasma spectrometer
February 2010

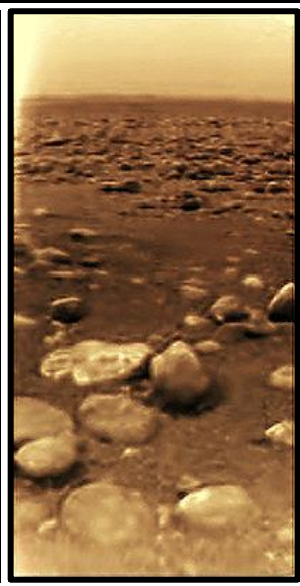


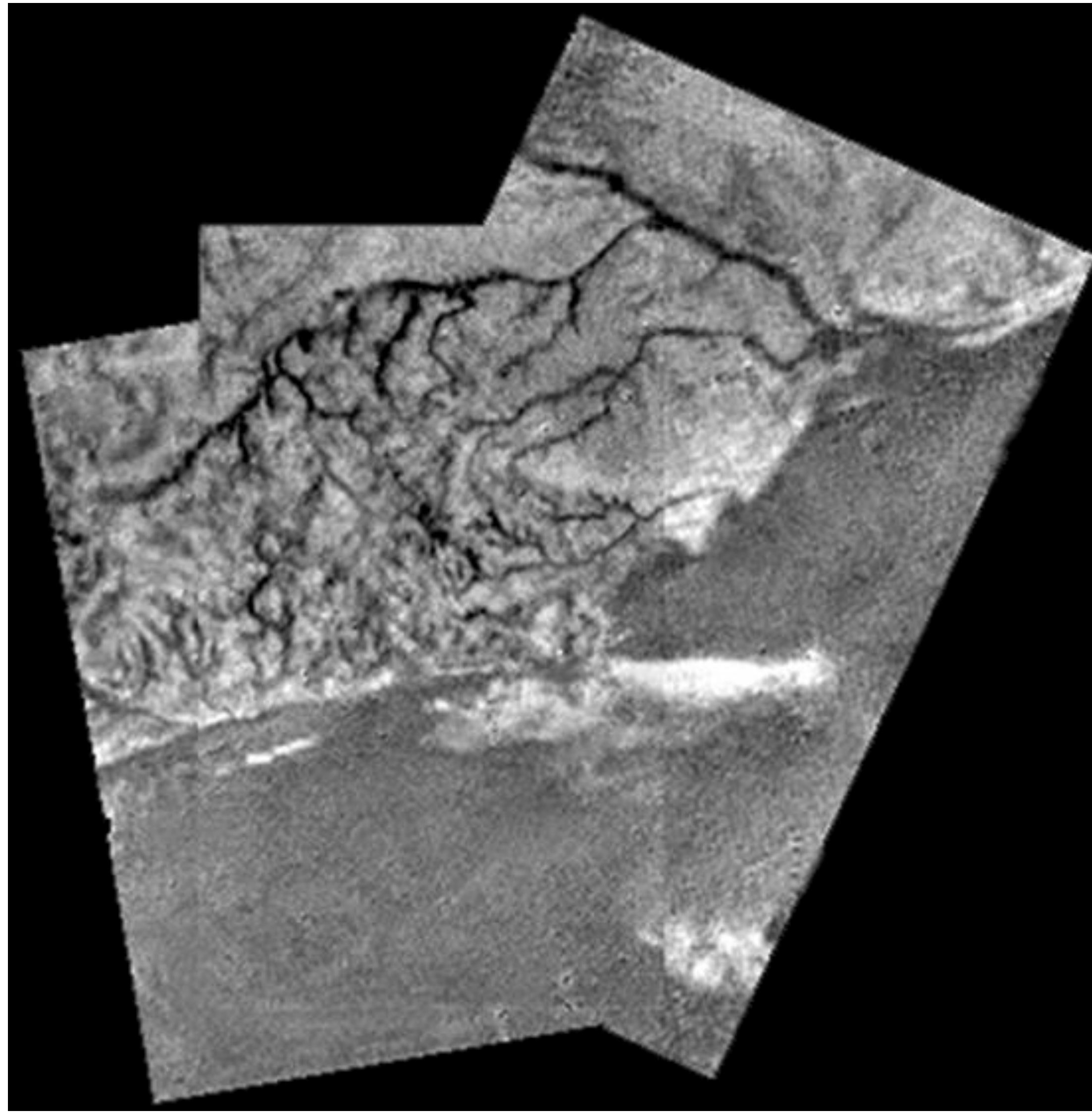
Iapetus ridge: 1,300 km long
Up to 13 km high in places …
Tidal bulge?

Landing on Titan



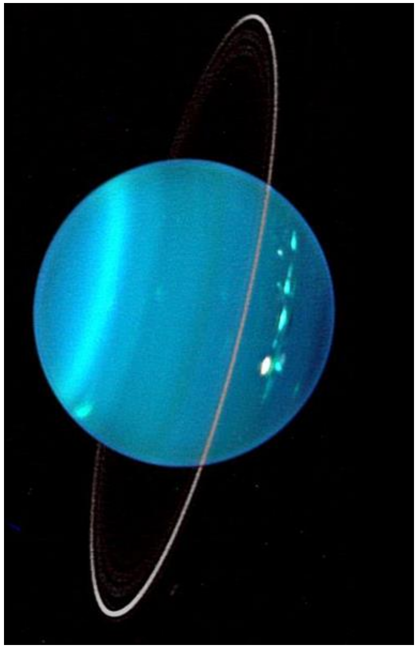






European Space Agency: Huygens lander, 2005

Uranus



IR composite

4 times larger than Earth – 19.8 A.U. from Sun
(plus the rings)

Orbits the Sun in 84 years
1 Uranus day = 17 hours

Atmosphere: mostly H_2, He
CH_4 (blue colour), H_2O, ammonia
Huge winds (> 500 m/s)

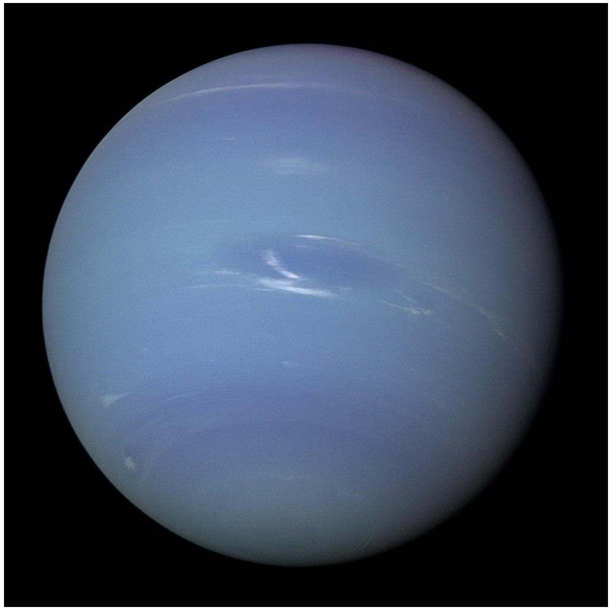
Ice giant
> 80% hot dense fluid of "icy" materials
(H_2O, CH_4, ammonia)
Small rocky core (4,982°C, cooler than others)

Tilted magnetic field – 27 moons, 13 rings

First planet discovered with telescope (Bath, 1781)

Voyager 2 was the only mission that studied Uranus (in the late 1980s)

Neptune



© NASA

A bit bigger than Uranus – 30.1 A.U. from Sun
(plus the rings)

Orbits the Sun in 164.8 years
1 Uranus day = 18 hours

Atmosphere: mostly H_2, He
Hydrocarbons and nitrogen?
Huge winds (< 580 m/s)
Cloud tops: 55 K

Ice giant
Small rocky core (5,100°C, cooler than others)

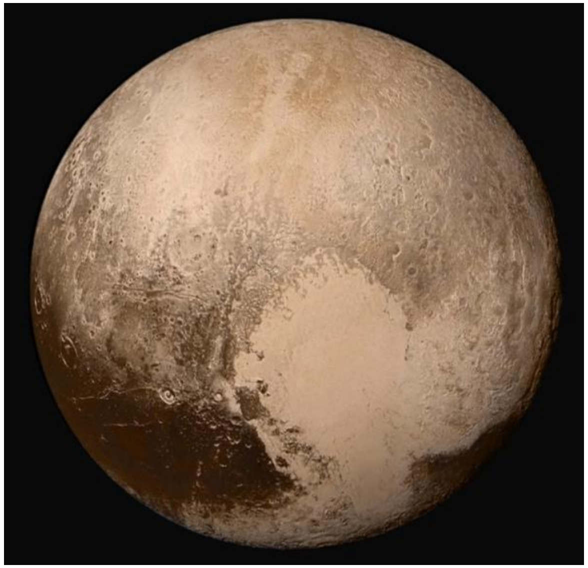
Tilted magnetic field – 14 moons, fragmented ring system

Strongest weather patterns in Solar System (wind speeds < 2,100 km/h)
First planet discovered from mathematical predictions (Le Verrier + Adams, 1846)

Voyager 2 was the only mission that studied Uranus (in the late 1980s)

Dwarf planets

Pluto



1/6th size of Earth, 39 AU from Sun

5 moons

Discovered 1930

NASA New Horizons close-by July 2015

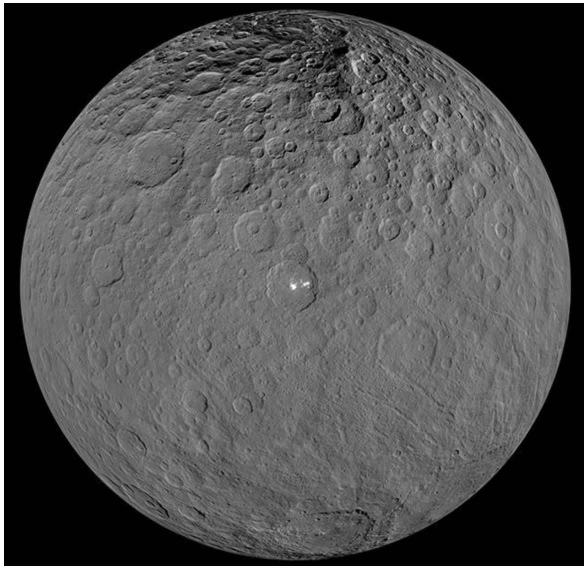
Orbits the Sun in 248 years

1 Pluto day = 153 hours

Rocky core and mantle of water ice

CH_4 and N_2 frost, sublimates when closer to Sun to form thin atmosphere

Ceres



1/13th size of Earth, 2.8 AU from Sun (between Mars and Jupiter)

Discovered 1801

NASA Dawn mission 2015

Orbits the Sun in 4.6 years

1 Ceres day = 9 hours

Solid core and mantle of water ice

Water vapour + ice volcanoes

Hot off the press (Wednesday)

Article

A dense ring of the trans-Neptunian object Quaoar outside its Roche limit

https://doi.org/10.1038/s41586-022-05629-6

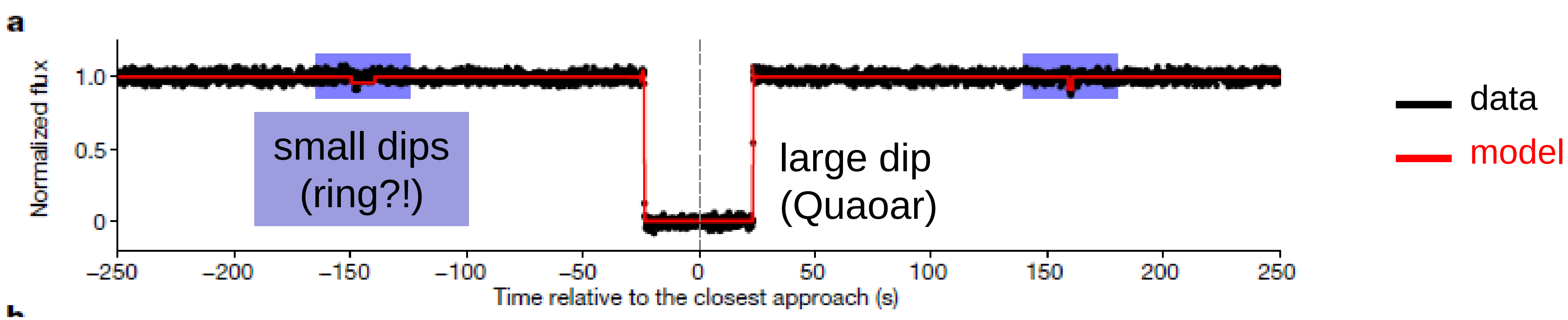
Received: 5 August 2022

Accepted: 6 December 2022

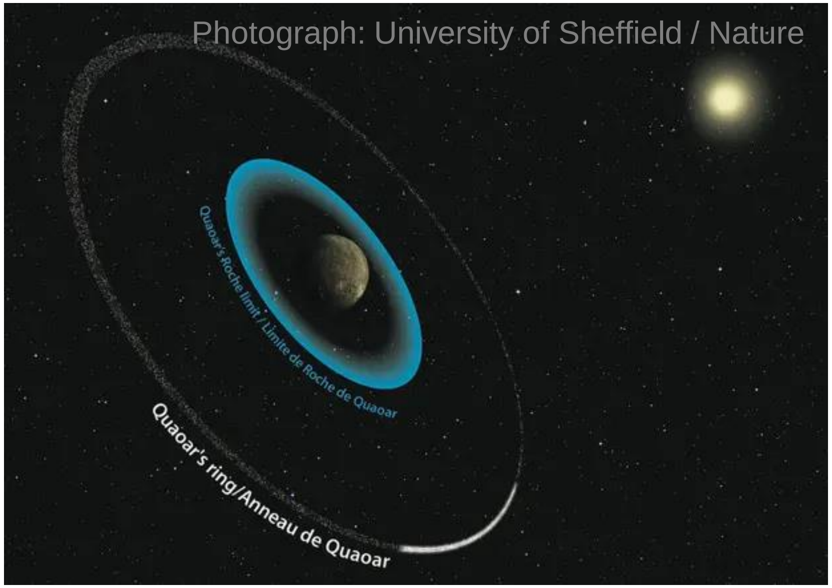
Published online: 8 February 2023

B. E. Morgado[1,2,3]✉, B. Sicardy[4], F. Braga-Ribas[5], J. L. Ortiz[6], H. Salo[7], F. Vachier[8], J. Desmars[8,9], C. L. Pereira[2,3], P. Santos-Sanz[6], R. Sfair[10,11], T. de Santana[4,11], M. Assafin[1,3], R. Vieira-Martins[2,3], A. R. Gomes-Júnior[3,11,12], G. Margoti[5], V. S. Dhillon[13,14], E. Fernández-Valenzuela[15], J. Broughton[16,17], J. Bradshaw[18], R. Langersek[19], G. Benedetti-Rossi[3,11], D. Souami[4,20,21], B. J. Holler[22], M. Kretlow[6,23,24], R. C. Boufleur[2,3], J. I. B. Camargo[2,3], R. Duffard[6], W. Beisker[23,24], N. Morales[6], J. Lecacheux[4], F. L. Rommel[2,3], D. Herald[17], W. Benz[25,26], E. Jehin[27], F. Jankowsky[28],

Observation of stellar occultations by this dwarf planet
(similar to exoplanet studies)



https://www.nature.com/articles/s41586-022-05629-6



The Roche limit is the distance at which an orbiting body will disintegrate because tidal forces exceed its own gravity:

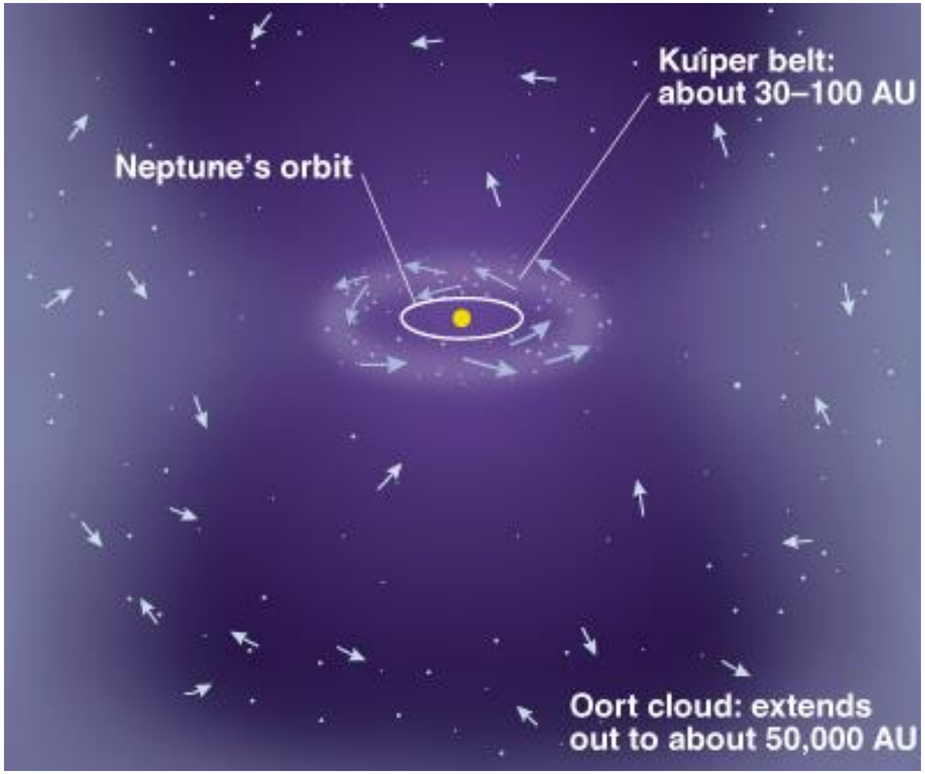
$$d = R_M \left(2 \frac{\rho_M}{\rho_m} \right)^{\frac{1}{3}} \ (rigid\ bodies)$$

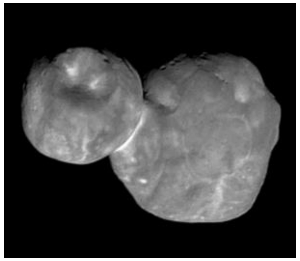
$$d \cong 2.44\ R_M \left(\frac{\rho_M}{\rho_m} \right)^{\frac{1}{3}} \ (fluid\ bodies)$$

Derived theoretically in 1848.

Planetary rings are observed not only around giant planets[1], but also around small bodies such as the Centaur Chariklo[2] and the dwarf planet Haumea[3]. Up to now, all known dense rings were located close enough to their parent bodies, being inside the Roche limit, where tidal forces prevent material with reasonable densities from aggregating into a satellite. Here we report observations of an inhomogeneous ring around the trans-Neptunian body (50000) Quaoar. This trans-Neptunian object has an estimated radius[4] of 555 km and possesses a roughly 80-km satellite[5] (Weywot) that orbits at 24 Quaoar radii[6,7]. The detected ring orbits at 7.4 radii from the central body, which is well outside Quaoar's classical Roche limit, thus indicating that this limit does not always determine where ring material can survive. Our local collisional simulations show that elastic collisions, based on laboratory experiments[8], can maintain a ring far away from the body. Moreover, Quaoar's ring orbits close to the 1/3 spin–orbit resonance[9] with Quaoar, a property shared by Chariklo's[2,10,11] and Haumea's[3] rings, suggesting that this resonance plays a key role in ring confinement for small bodies.

And beyond …

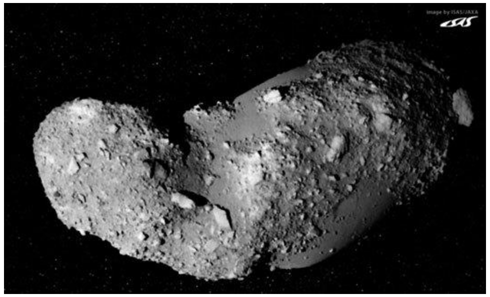




Ultima & Thule

Trans-Neptunian objects

1st Jan. 2019



Asteroid Itokawa

sample return 2015

1I/2017 U1

'Oumuamua

detected 10/2017

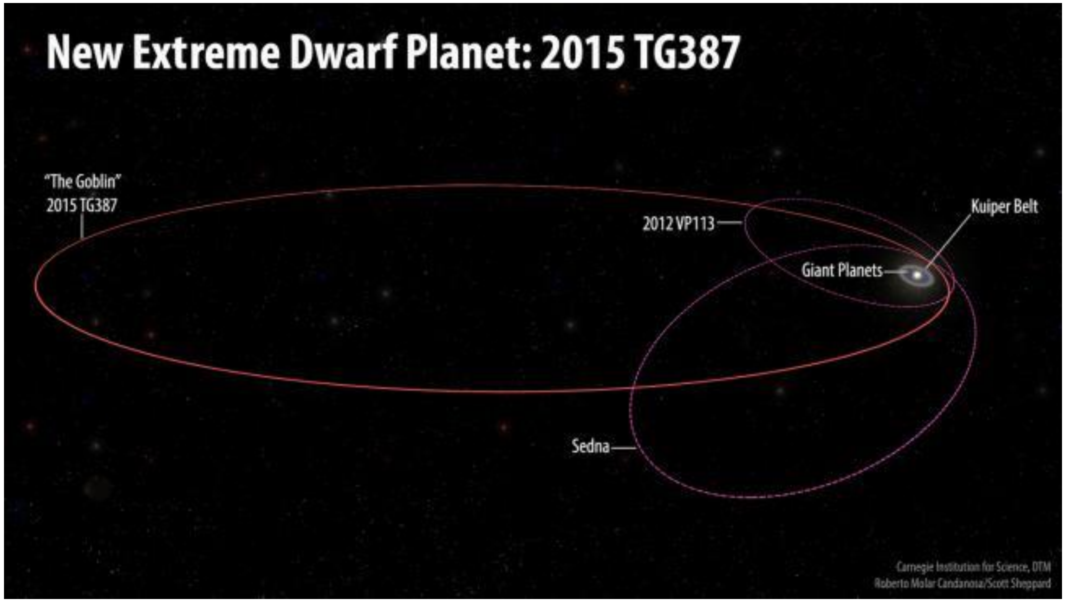
<u>Other objects include:</u>

comets (from the Oort cloud)

asteroids (everywhere)

interstellar objects (only 1 confirmed so far)

And beyond …



2015 TG 387 "The Goblin"

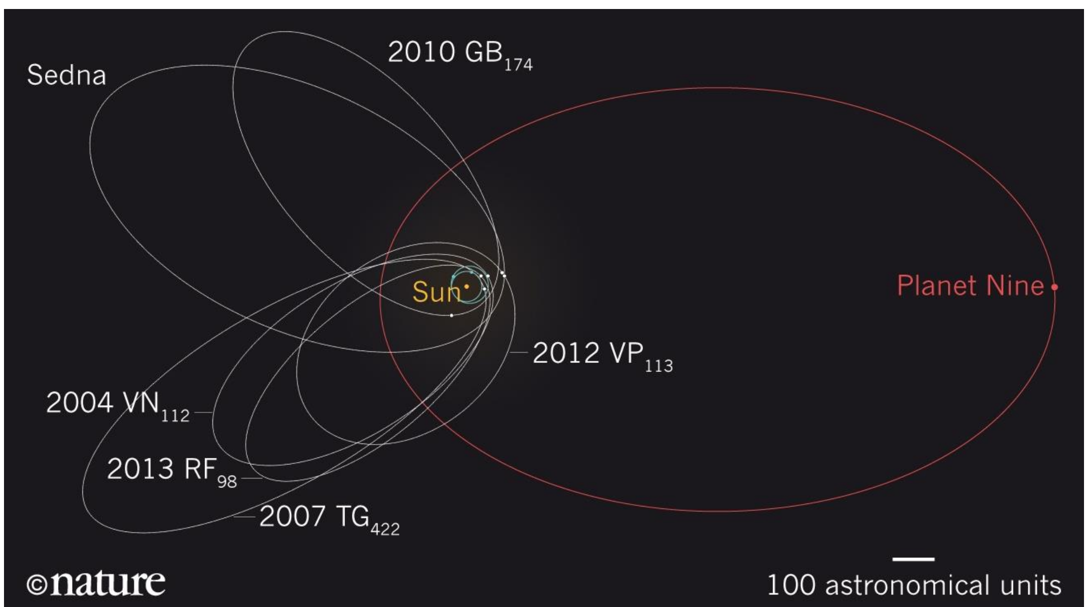
very elongated orbit

(65 – 2,300 AU)

orbital period: 32,000 years

diameter: 300 km

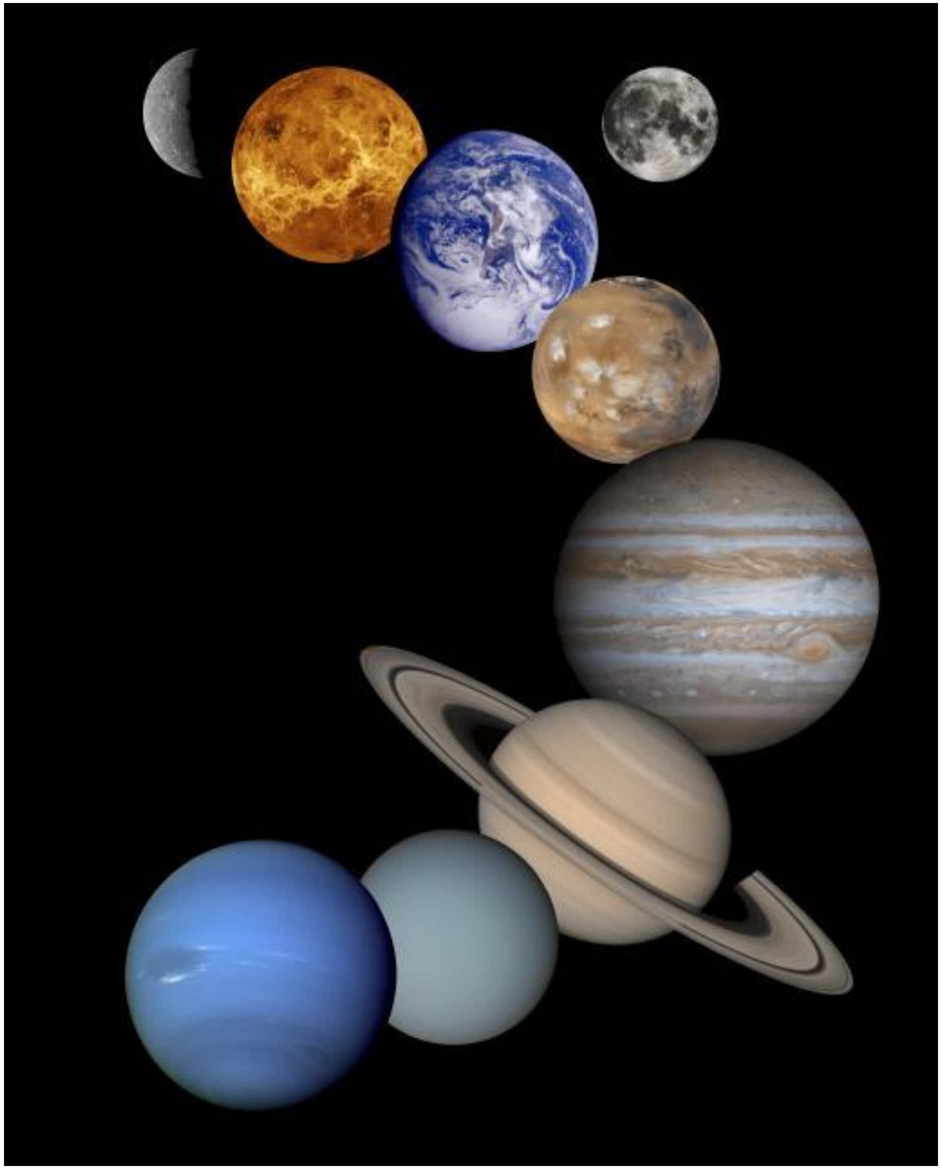
Detected in 2015, validated and announced in October 2018



Similar objects and orbits are used to search for hypothetical "Planet Nine"

(Batygin & Brown, 2016)

Summary



© NASA

Variations in planets:

surface (or not)
atmosphere (or not)
magnetosphere (or not)

Variations in elements (e.g. water)

Very few missions but most discoveries within last decades

Some earlier datasets (e.g. 1990s) still contain important data not processed/interpreted yet

More data to come

What kind of Physics can we use?

Summary

Discoveries	Challenges	Physics
Transitions: rocky planets to gas and ice giants	Planetary formation theories “Snow line”?	Gravity and mechanics Extreme T, P
Atmospheres	What are they made of? Vertical variations Weather patterns Chemical anomalies?	Spectroscopy Radar and Doppler Ground observations
Surfaces	Compositions Volcanism/tectonics Unusual structures	Optical imaging Radar imaging (below clouds)
Planet evolutions	Relative vs. absolute dates of surfaces/atmospheres	Impact cratering Radioactive decays Direct sampling
Sub-surface	Buried deposits? Differentiation	Moments of Inertia Seismics (quakes) Impact craters
Magnetospheres	Influence on planets and their moons	Direct measurements Indirect evidence (auroras …)