Voyage to the Planets
Lecture 8:
The outer solar system

Uranus, Neptune and (minor) planets beyond

Presented by

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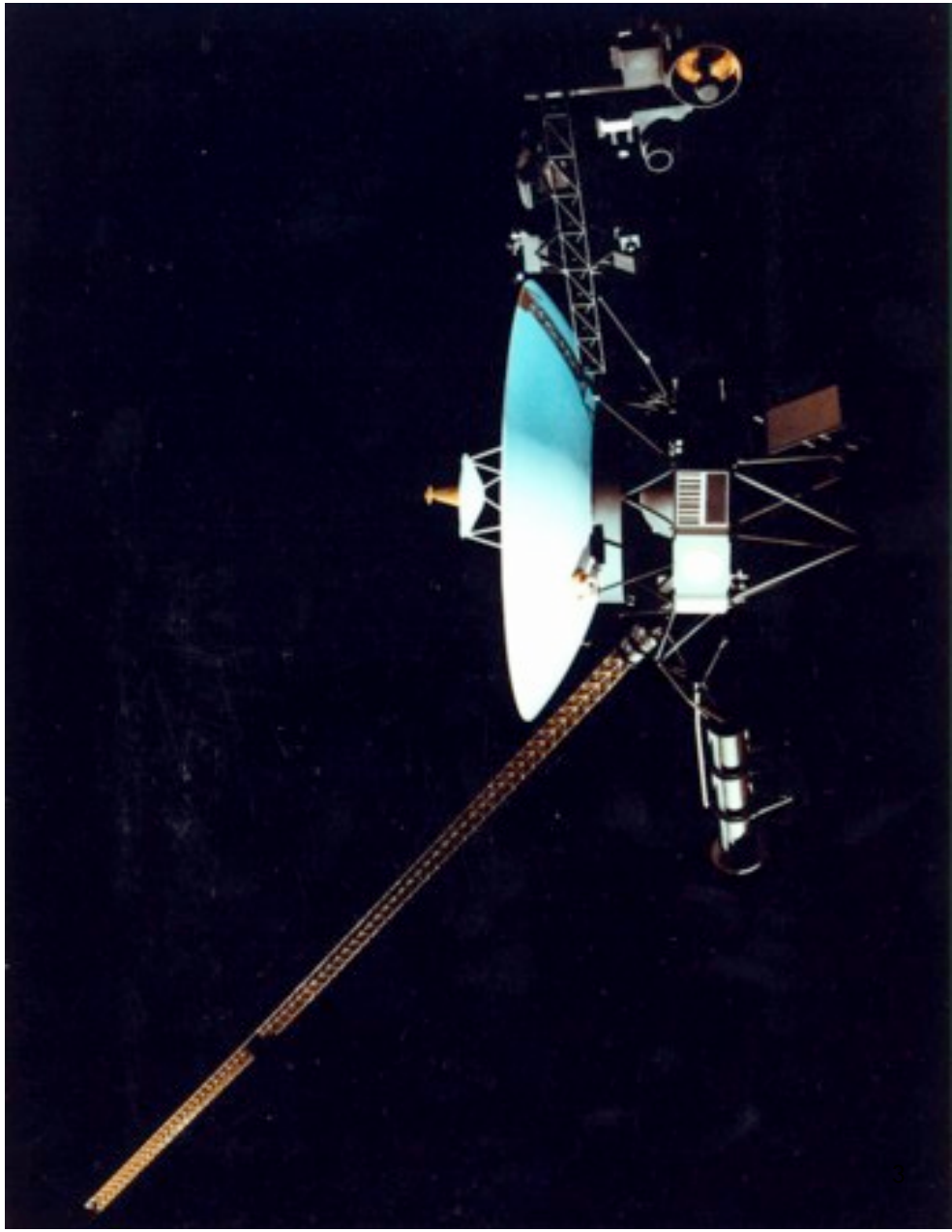
THE UNIVERSITY OF SYDNEY

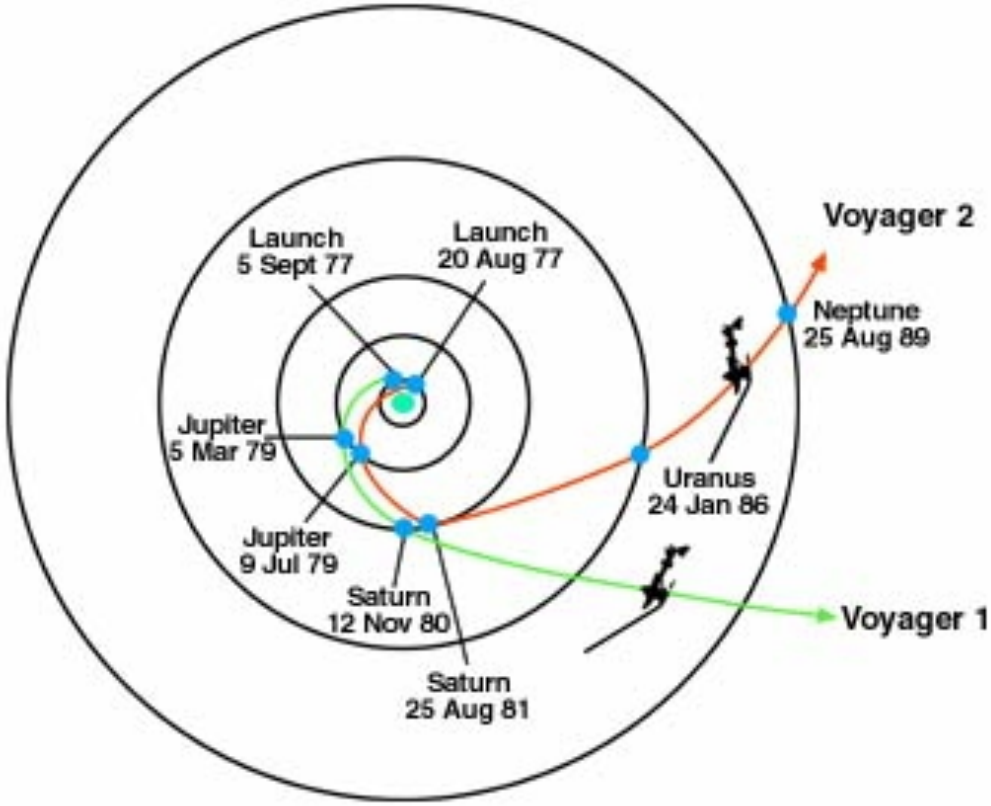
Tonight

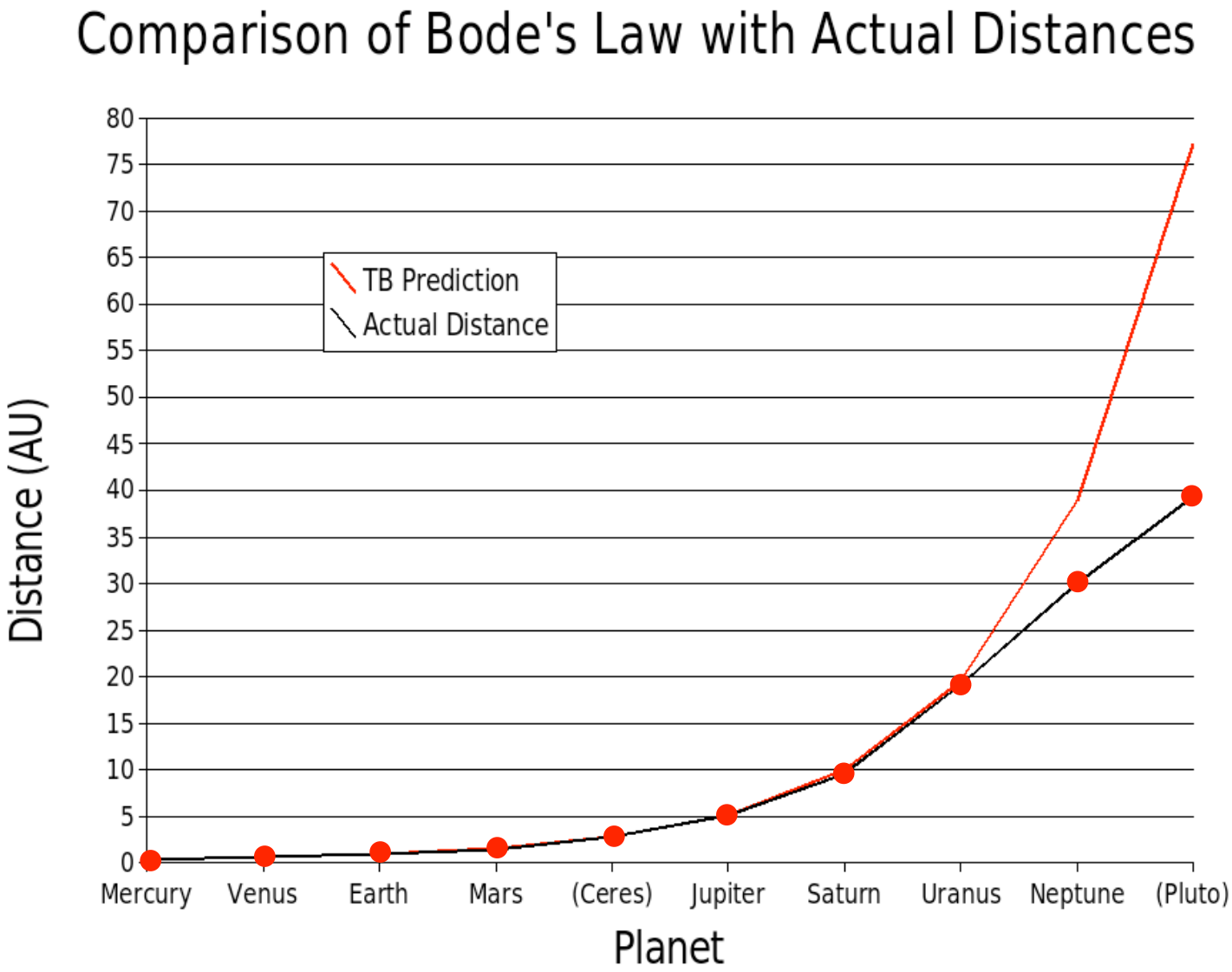
- Uranus
- Neptune
- Pluto and Charon
- Eris, and beyond

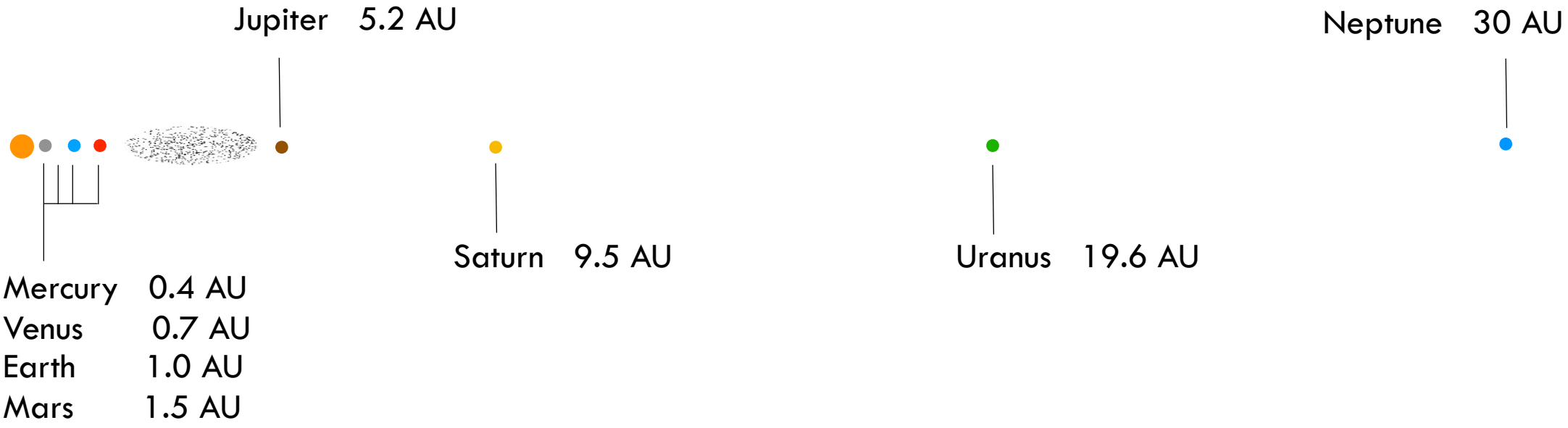
The only mission to fly to the outer planets was *Voyager 2*. After leaving Saturn in August 1981, *Voyager* arrived at Uranus in January 1986, then flew on past Neptune in August 1989. It then swung down below the ecliptic and headed into interstellar space.



The *Voyager* missions took advantage of a once-every-175-year planetary alignment, which allowed a spacecraft to use multiple gravity assists to reach all the outer planets. It reduces the time taken from 30 years (for a direct flight to Neptune) to 8–13 years using gravity assists. Launch windows were available between 1976 and 1980; both *Voyager* spacecraft were launched in 1977.



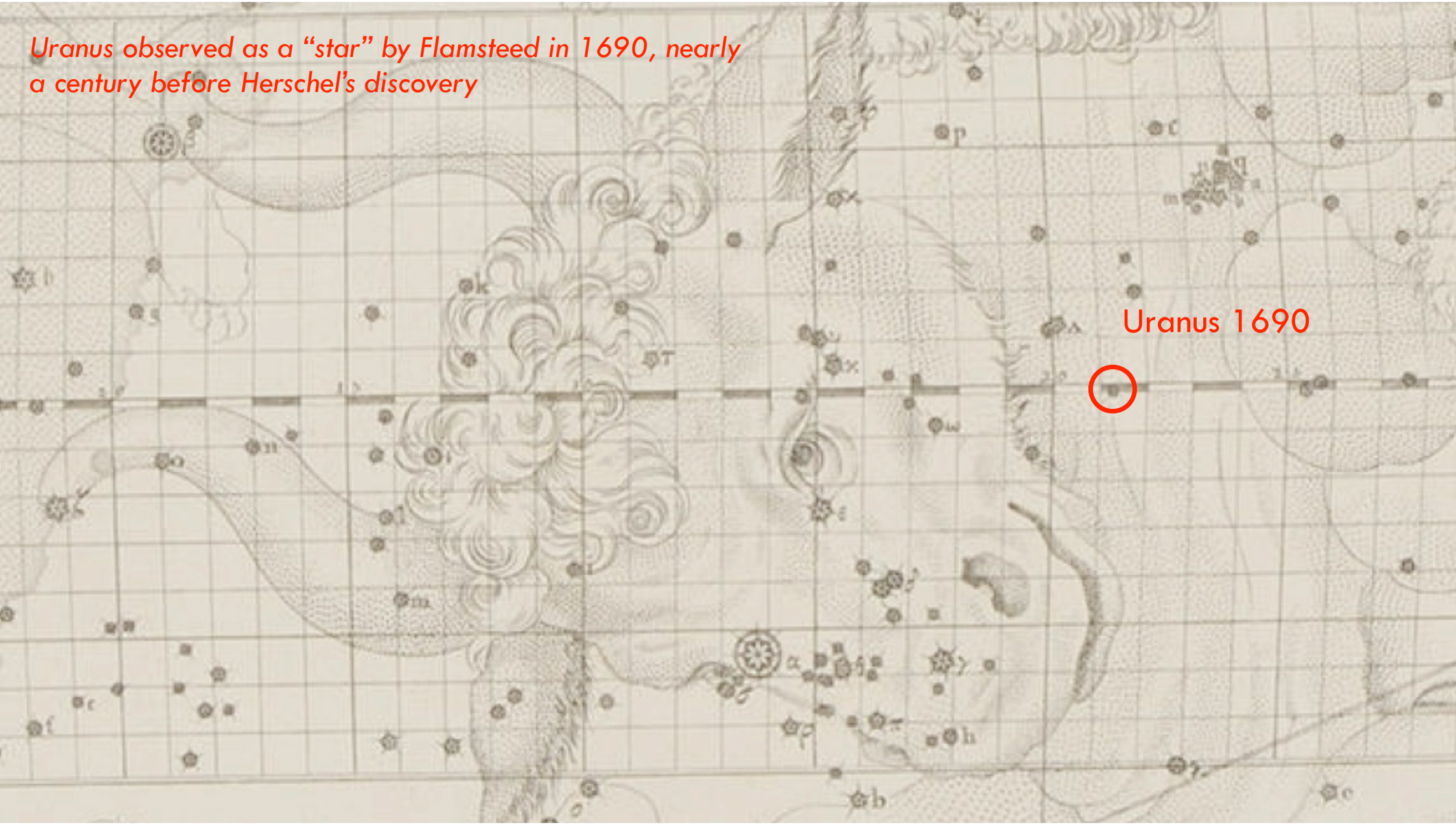

Comparison of Bode's Law with Actual Distances
Distance (AU)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
TB Prediction
Actual Distance
Mercury
Venus
Earth
Mars
(Ceres)
Jupiter
Saturn
Uranus
Neptune
(Pluto)
Planet


Jupiter 5.2 AU
Neptune 30 AU
Saturn 9.5 AU
Uranus 19.6 AU
Mercury 0.4 AU
Venus 0.7 AU
Earth 1.0 AU
Mars 1.5 AU

Uranus

Uranus was discovered in 1781 by William Herschel, musician and amateur astronomer. Herschel became the first person in recorded history to discover a new planet, at a stroke doubling the size of the known Solar System.

In fact, Uranus had been detected, mistaken for a star, on 22 occasions during the preceding century, including by John Flamsteed, the first Astronomer Royal, who called it 34 Tauri.

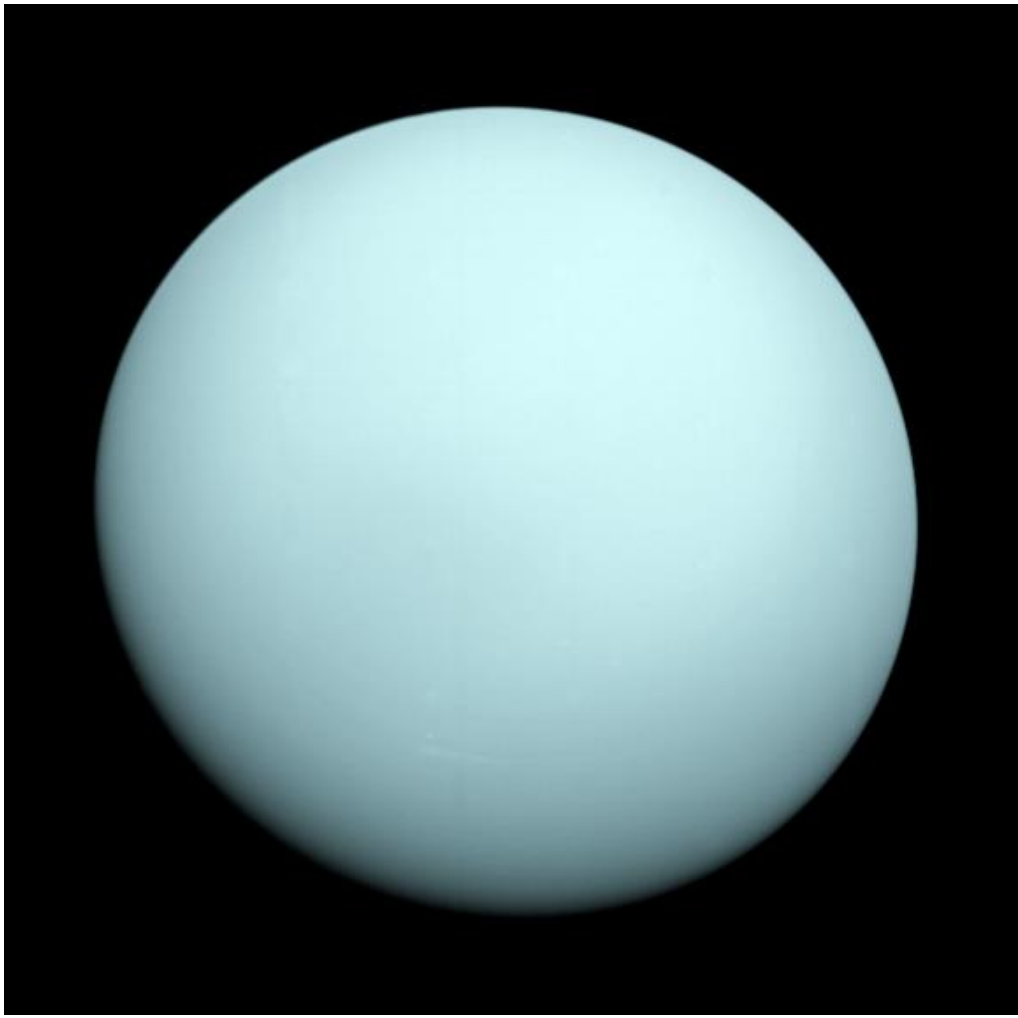

Uranus observed as a “star” by Flamsteed in 1690, nearly a century before Herschel’s discovery
Uranus 1690

Basic data

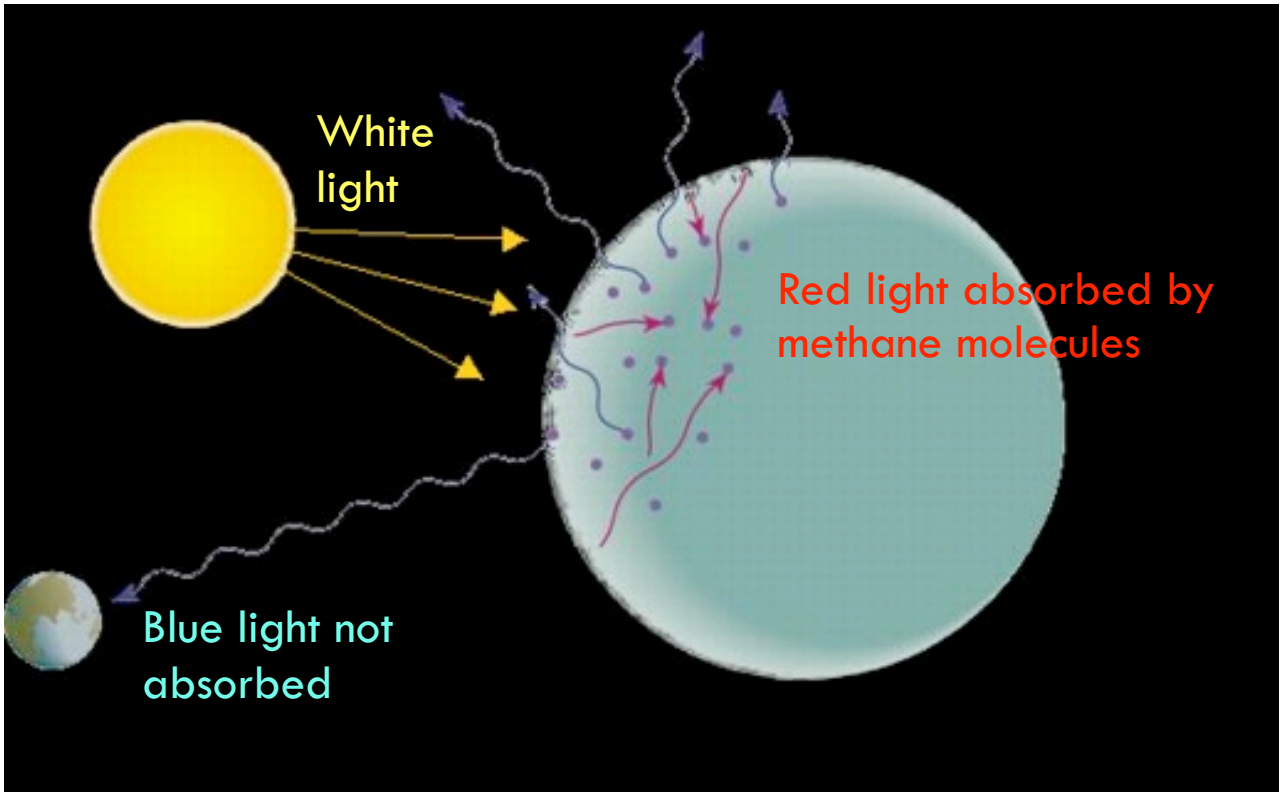
	Uranus	Uranus/Earth
Mass	86.83×10^{24} kg	14.536
Radius	25,559 km	4.007
Mean density	1.270 g/cm^3	0.23
Gravity (eq., 1 bar)	8.87 m/s^2	0.905
Semi-major axis	2872×10^6 km	19.2
Period	30 685.4 d	84.011
Orbital inclination	0.772°	-
Orbital eccentricity	0.0457	2.737
Axial tilt	97.8°	4.173
Rotation period	–17.24 h	0.72

Uranus shows an almost totally featureless disk. Even *Voyager 2* at a distance of 80,000 km saw few distinguishable features.

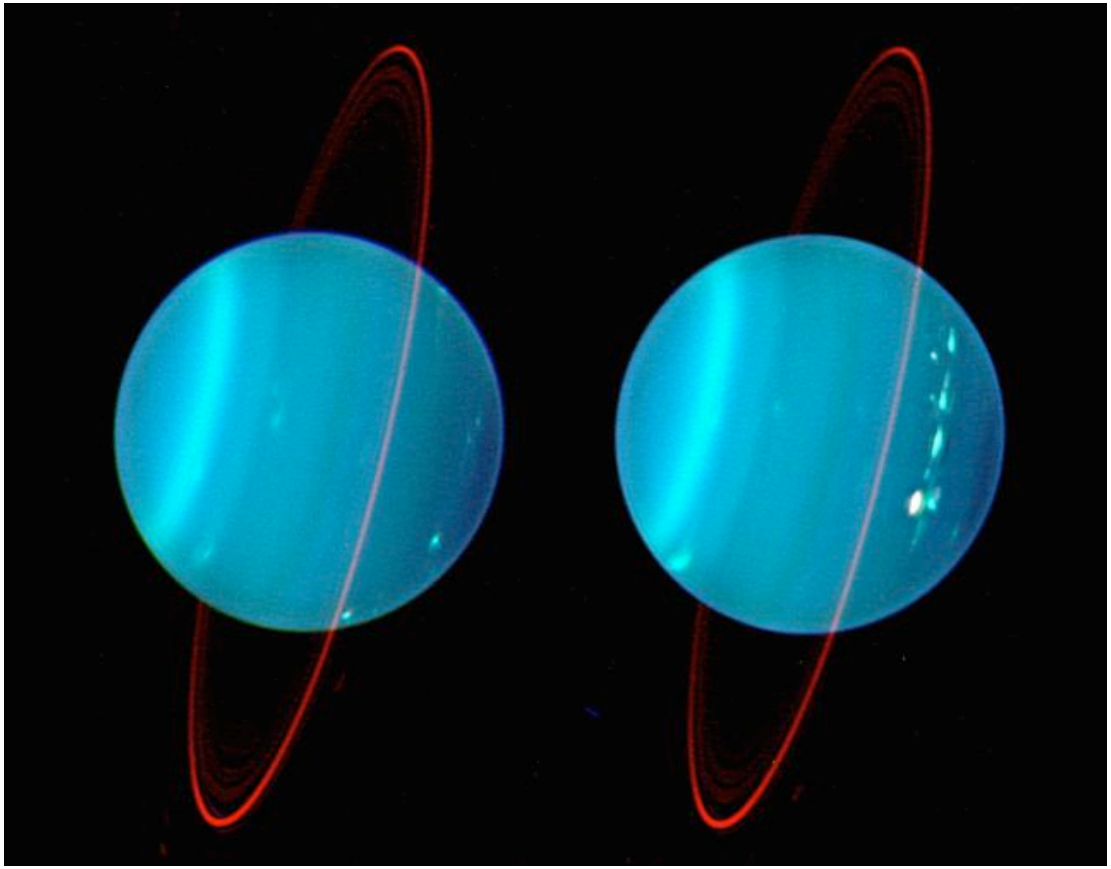
Uranus does not have as much internal heat as Jupiter or Saturn, so the convection currents in the atmosphere are not as strong. This explains why Uranus' atmosphere does not show clear bands.



Uranus' atmosphere is made up of 83% hydrogen, 15% helium, 2% methane and small amounts of acetylene and other hydrocarbons. Methane in the upper atmosphere absorbs the red light and gives Uranus its blue-greenish colour.

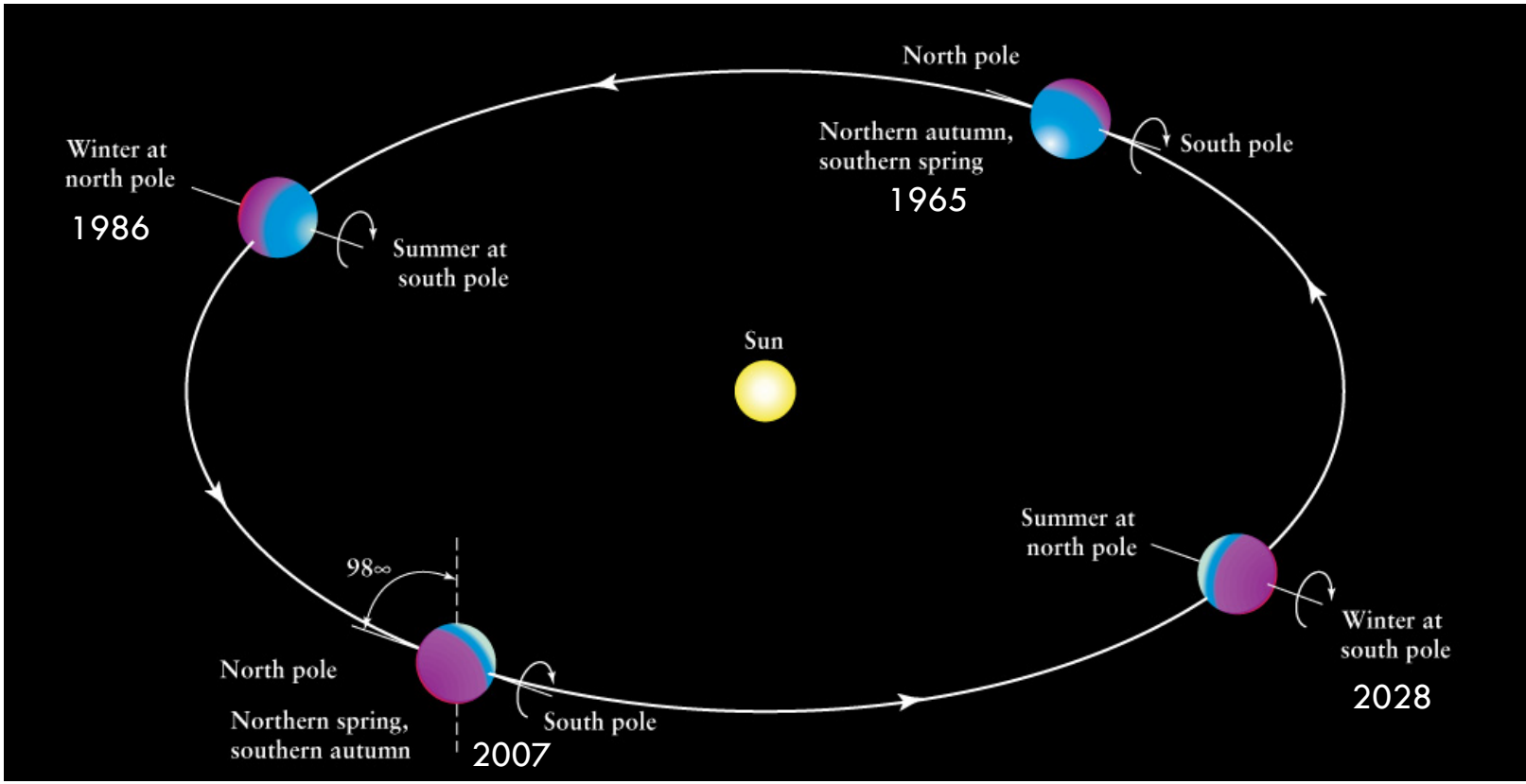


Unlike all the other planets, the rotation axis of Uranus is tilted to lie almost in the plane of its orbit. The equatorial plane is inclined 98°, so it spins backwards compared to other planets.



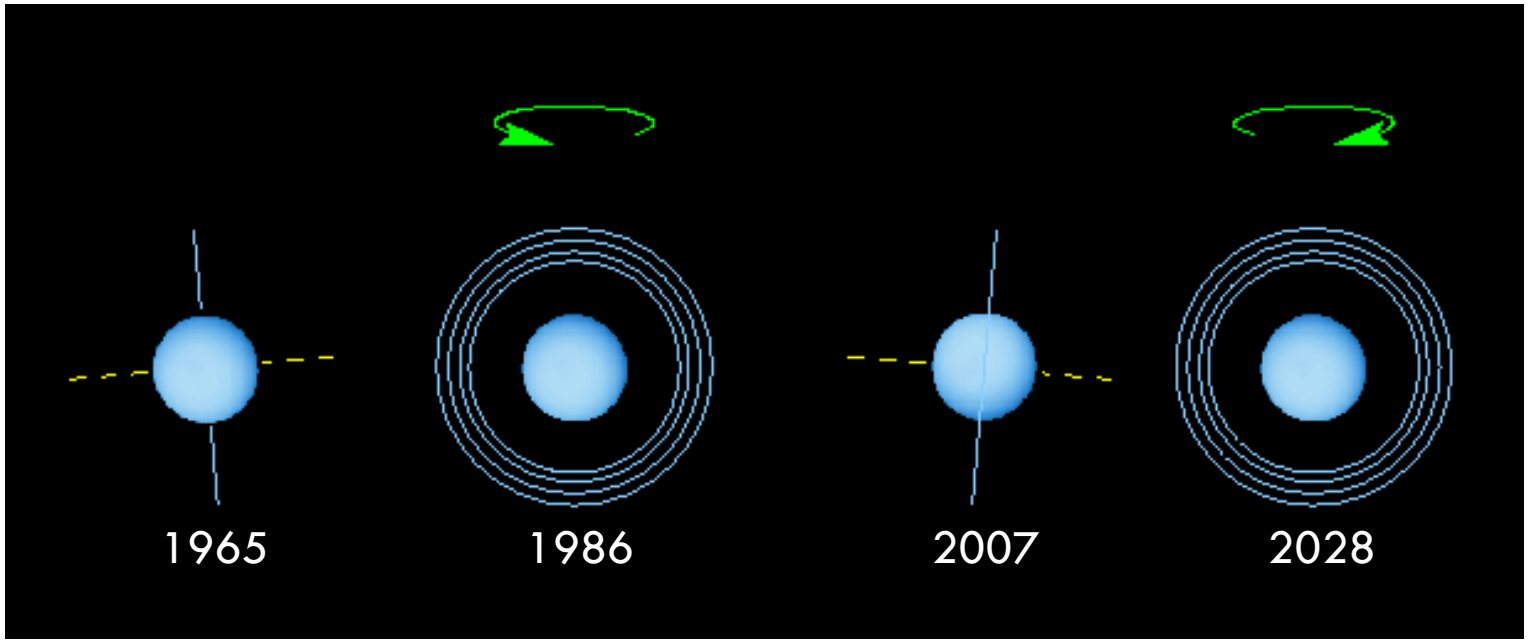
Infrared image taken by the Keck Telescope, showing layers in the atmosphere.

As a result of this tilt, Uranus has very bizarre seasons, with each pole being sunlit for 42 (Earth) years. During this time, the pole receives more light than the equator, before being plunged into darkness for the next 42 years.

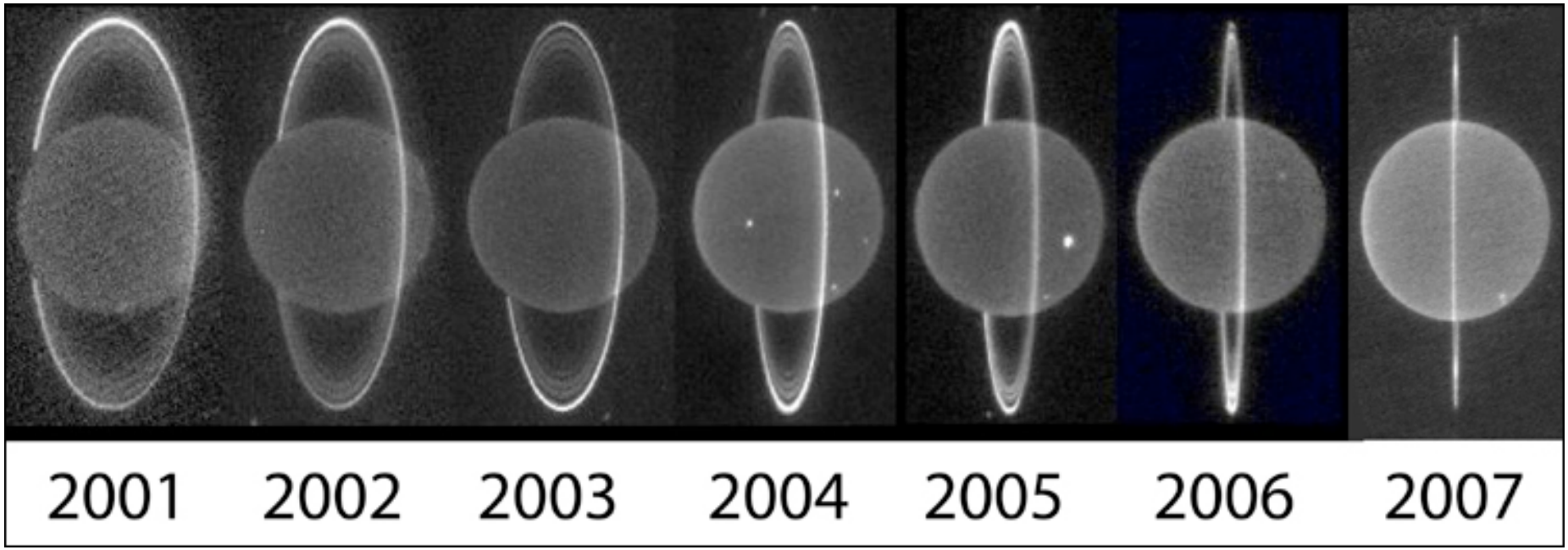


The *Hubble Space Telescope* saw enormous storms swirling around Uranus as the northern hemisphere came out of its 20-year winter.

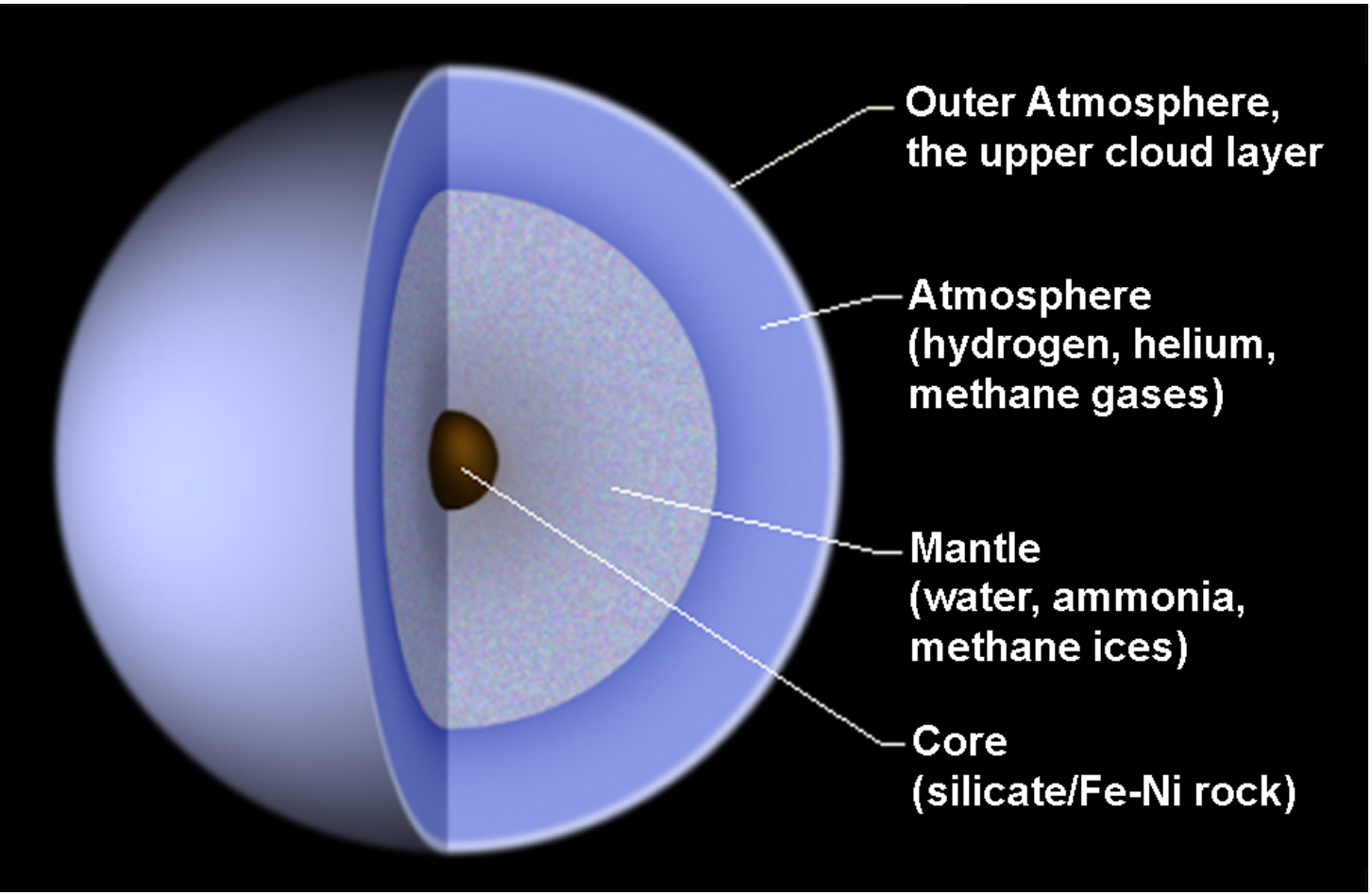
Since the axis of rotation always points to the same direction in space, at some points in its orbit its pole is pointed towards us, and sometimes it appears side-on to us. Uranus' equinox occurred in December 2007, at which time we saw Uranus' rings and moons side-on.



The changing view of Uranus since 2000, from Keck. As Uranus moved to present a more edge-on view of its rings, the rings became brighter and more distinct



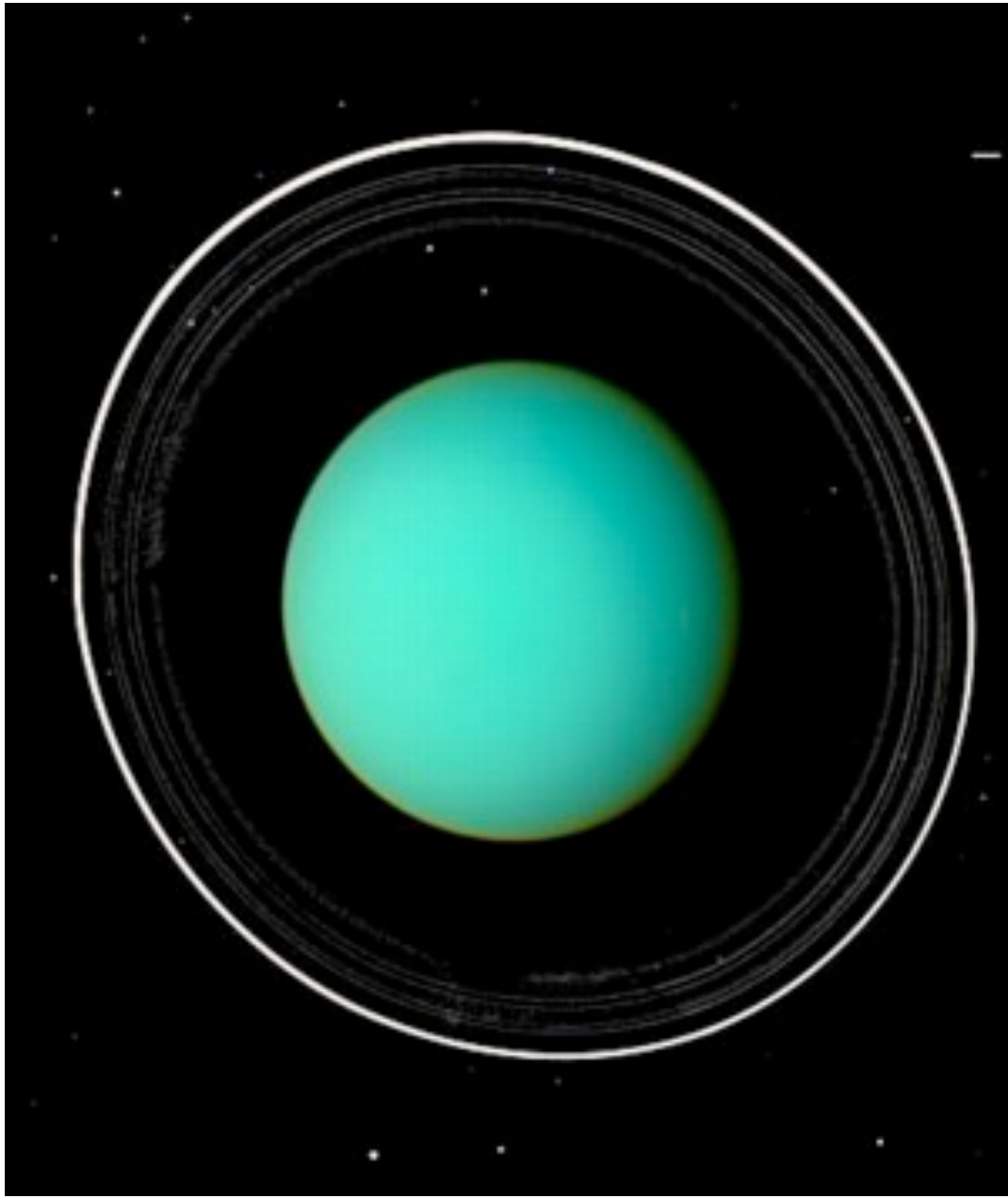
Like Jupiter and Saturn, Uranus has a rocky core. However, the pressure is high not enough to convert molecular hydrogen to metallic hydrogen in the interior. Instead, 80% of the mass of the planet consists of a mantle made up mostly of water with some methane and ammonia. The inner core is about 1 Earth mass, and the outer layer is a hydrogen and helium-rich atmosphere.



Uranus has rings which are narrow, widely separated, and eccentric, quite unlike those of Jupiter or Saturn. Most of them are less than 10 km in width. Unlike the icy rings of Saturn or the dusty rings of Jupiter, the particles in Uranus' rings are extremely dark, with albedos of only 2%, as dark as the blackest asteroids and meteorites. The rings are also clumpy, suggesting they are very young.

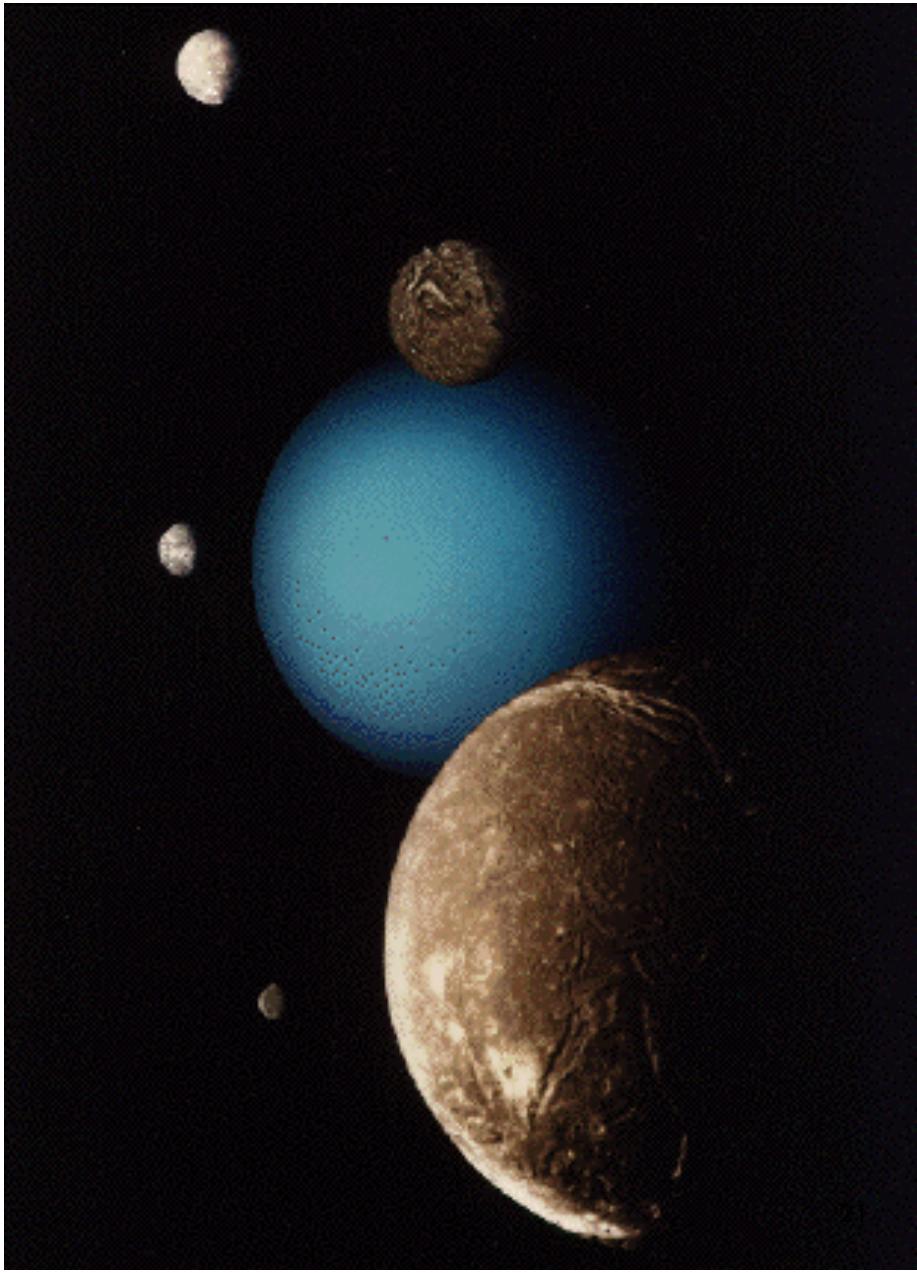
The brightest ring, Epsilon, orbits at a distance of just over twice Uranus' radius, or one radius above the surface. There are nine major rings: from the planet outwards, they are named 6, 5, 4, Alpha, Beta, Eta, Gamma, Delta, and Epsilon.

Voyager detected a few additional rings and also showed that the nine major rings are surrounded by belts of fine dust.



Uranus has at least 27 moons. Five are large, known prior to the space age: *Miranda*, *Ariel*, *Umbriel*, *Titania* and *Oberon*. All are much smaller than the Earth's Moon, ranging from 1/6th the size of the Moon (Miranda) to about half (Titania and Oberon).

Voyager discovered ten new moons, and Earth-based observations have added a few more. From their density, they appear to be mixtures of ice and rock, with some ammonia and methane.



Voyager's encounter at Uranus:

14:00 *Voyager* 230 000 km (10 Uranian radii) from Uranus

15:08 Closest to Titania (365 000 km)

16:12 Closest to Oberon (471 000 km)

16:20 Closest to Ariel (130 000 km)

17:03 Closest to Miranda (32 000 km)

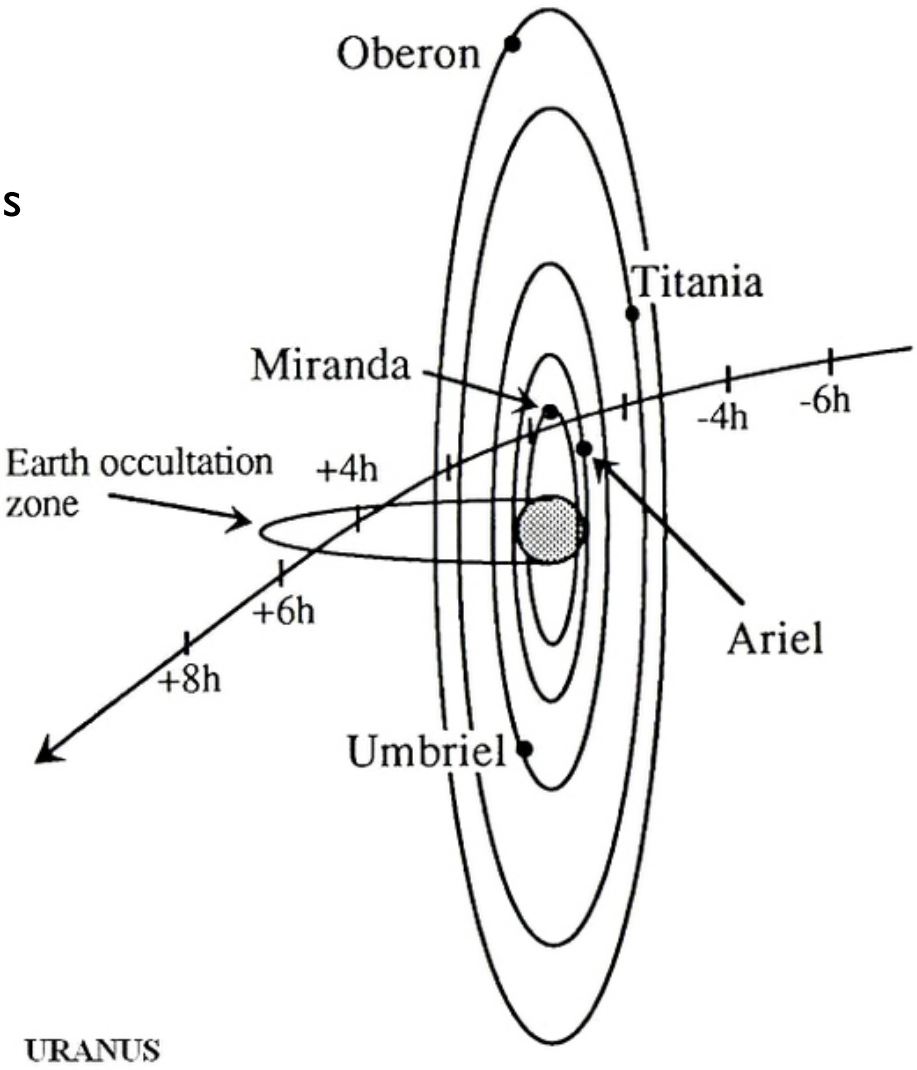
17:16 Ring-plane crossing

17:59 Closest to Oberon (471 000 km)

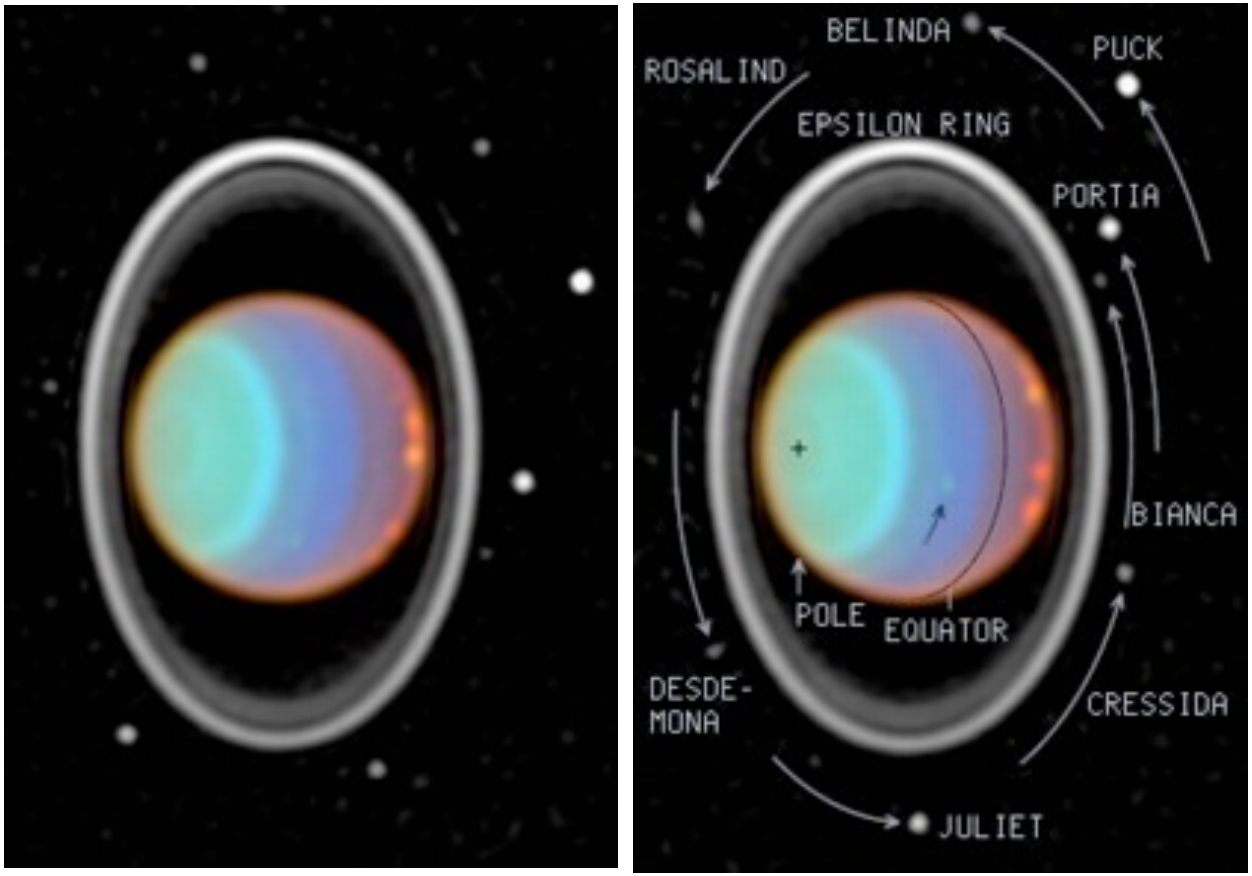
20:38 Occultation of *Voyager* by Uranus (till 22:45)

20:45 Closest to Umbriel (325 000 km)

24:00 *Voyager* now 650 000 km from Uranus

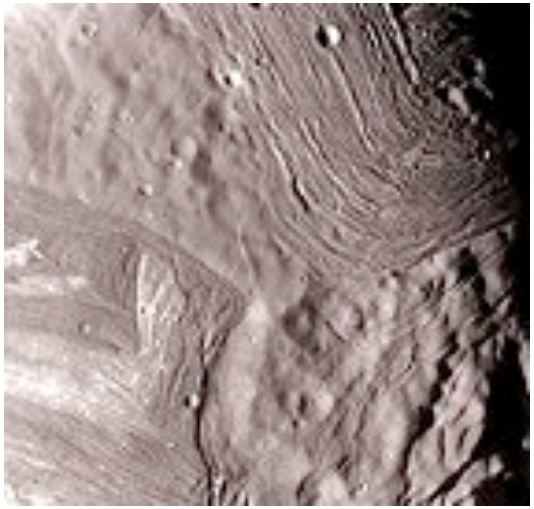


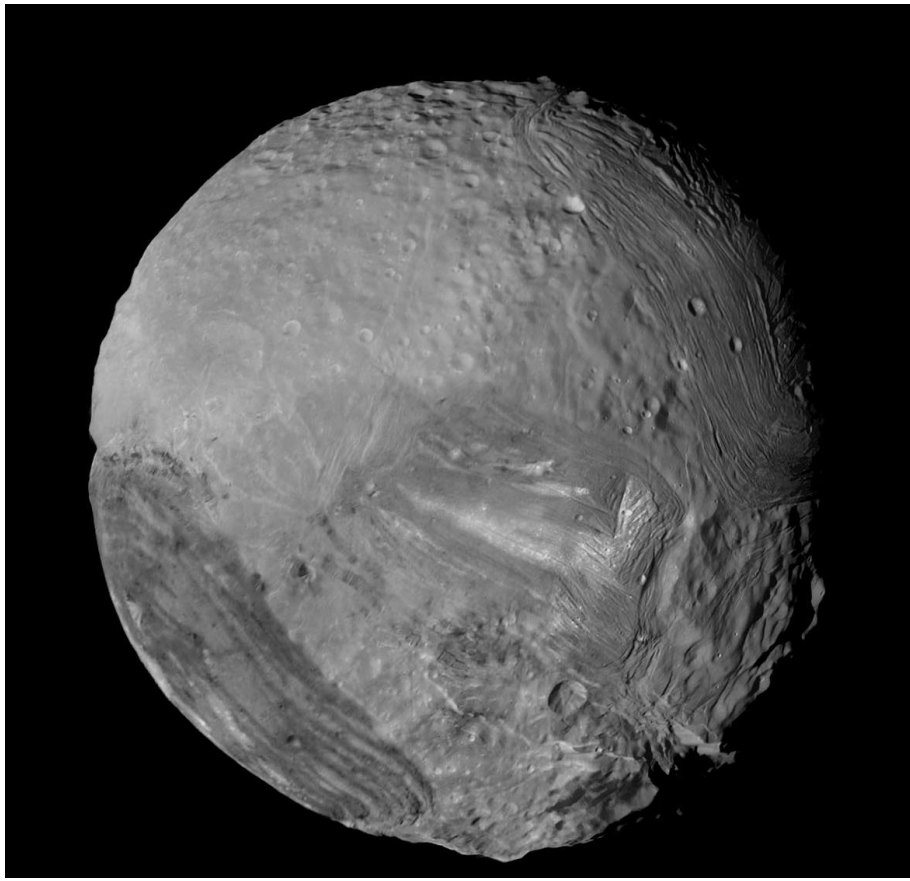
The moons are in Uranus' equatorial plane, like other planets: so unlike Jupiter's moons, which appear always in a line to us, during the past two decades we were able to see Uranus' moons (nearly) face on.



HST infrared images of Uranus, showing the rings and moons (which have moved over the 90 minutes between the two pictures).

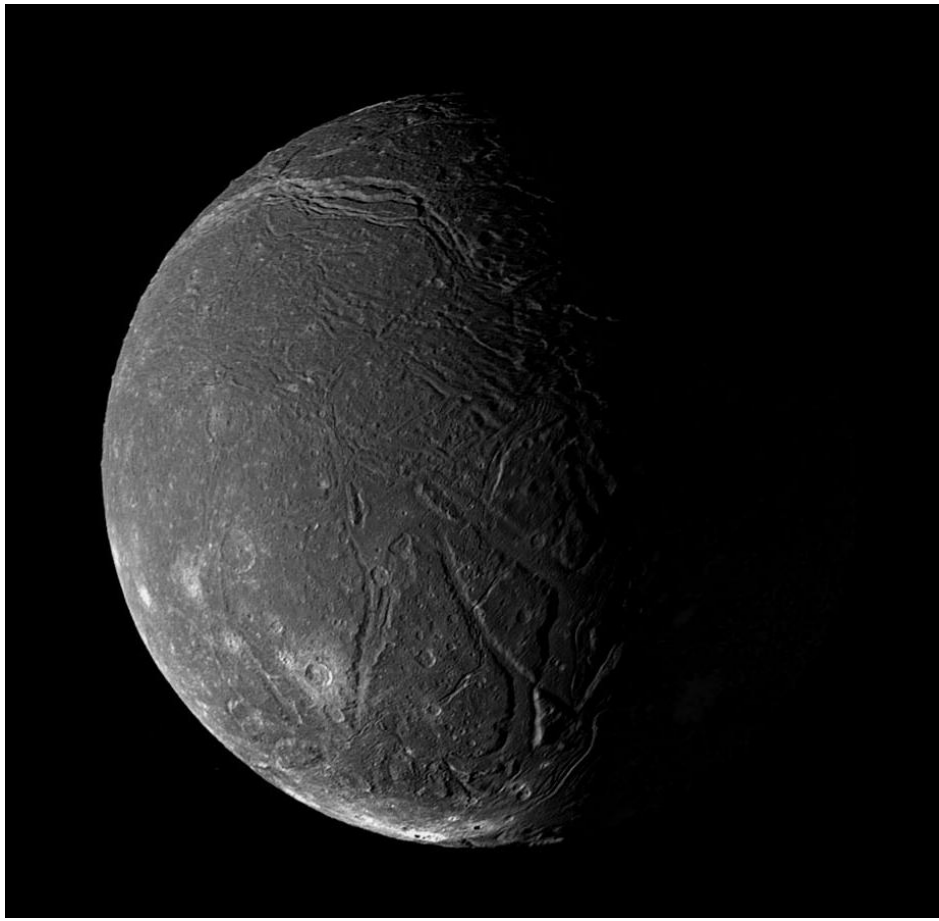
Miranda, the innermost of the five large moons, is only 470 km in diameter. Its surface looks as though it has been broken up and reassembled. It has huge fault canyons 20 km deep, layering and terraces, and old, pock-marked surfaces and young, bright regions. This suggests ice was melted and re-froze, though how this could happen when the temperature is –187° C is hard to understand. Possibly it was the result of the cataclysm which shattered the surface, and possibly the same one which tilted Uranus on its side.



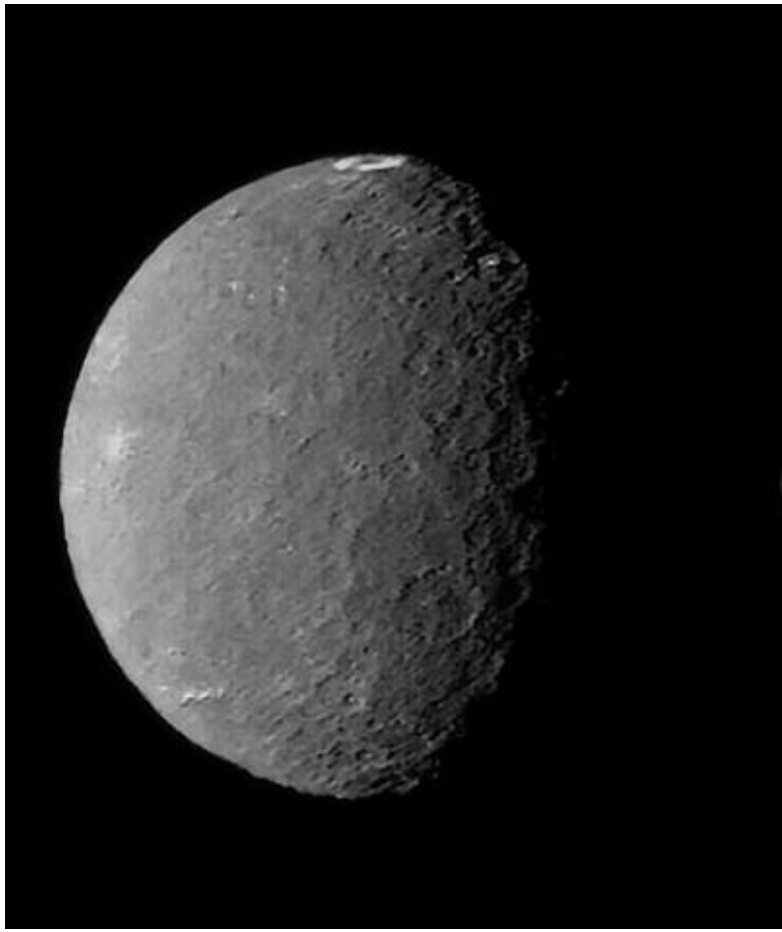


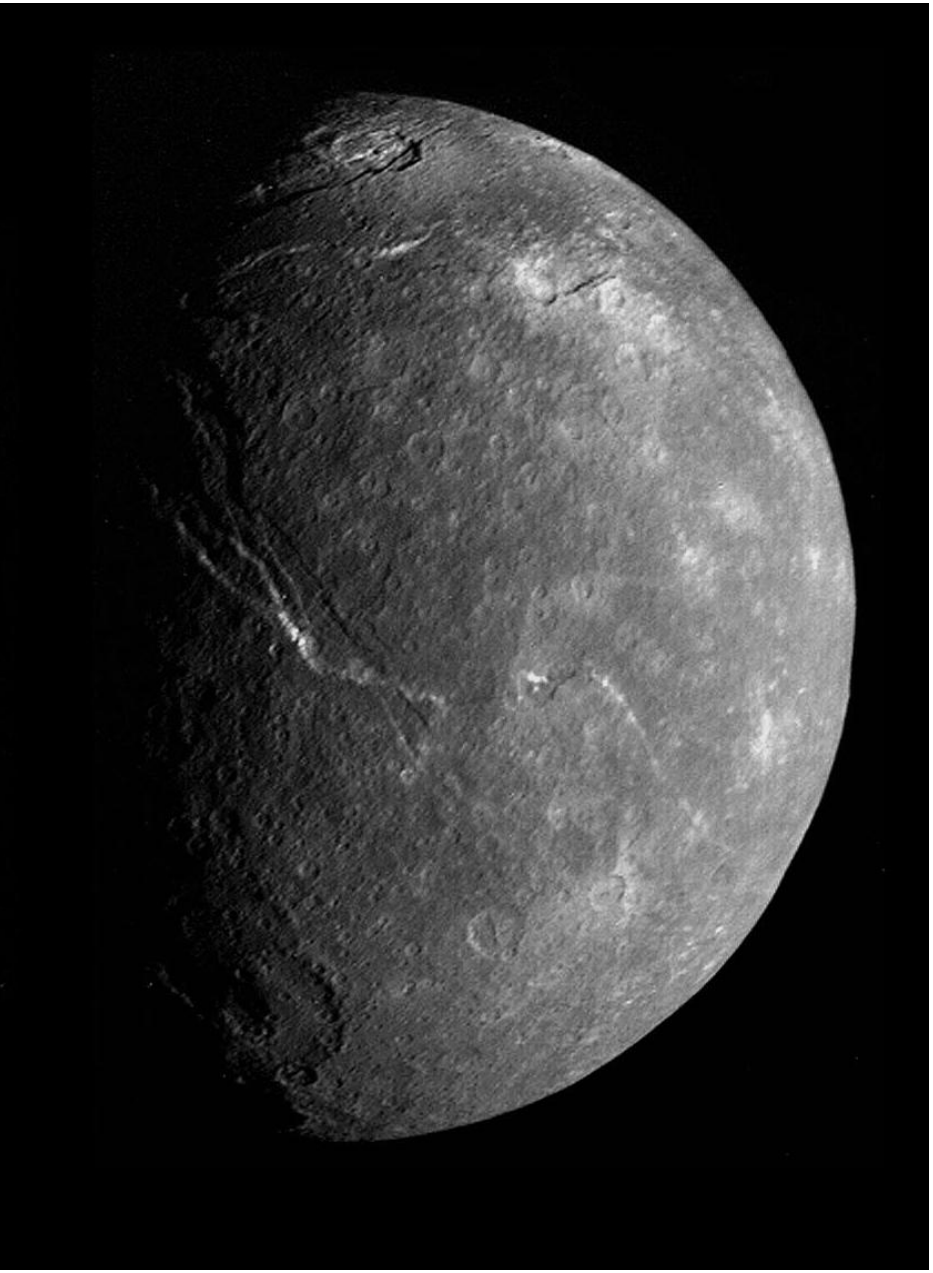
Ariel is covered with huge canyons, which look like faults produced by expansion and stretching of the crust. Some of the canyon floors appear to have been smoothed by liquid, presumably ammonia, methane or even carbon monoxide.

Much of the surface is marked by small, young craters (from their bright ejecta blankets).



Umbriel, which is almost exactly the same size as Ariel, is darker, shows no major rift features, and is covered with craters of all sizes, including the bright ring at the top called the *fluorescent cheerio*, which is probably the floor of a crater. Possibly Ariel, but not its sibling Umbriel, was remelted by some process which led to cracking of the icy crust and the release of molten water.



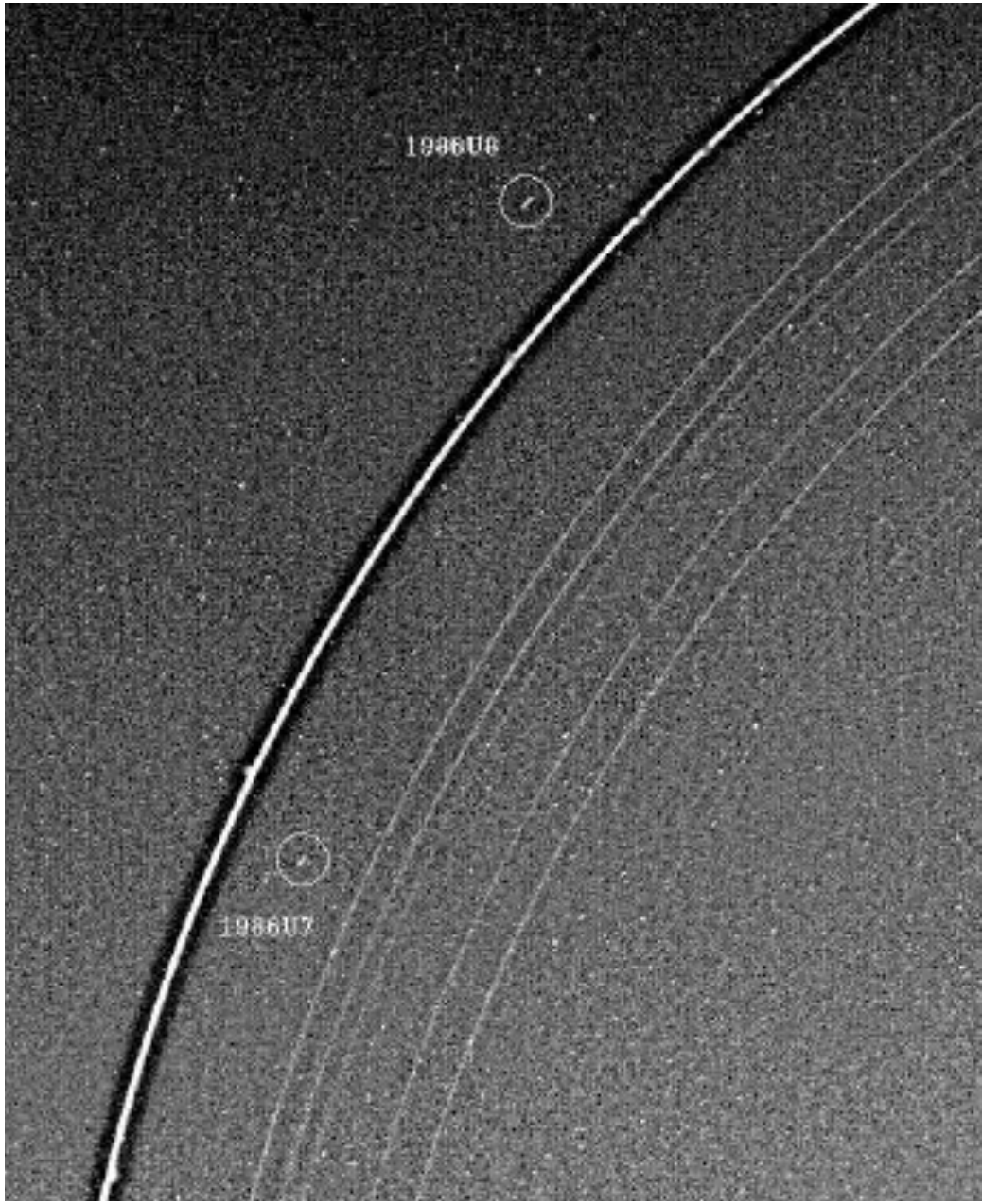


Titania, the largest of Uranus' moons, has a few large impact basins, but is mostly covered with small craters and very rough rocks. It has huge fault systems and canyons that indicate that internal forces have been active in moulding its surface. A large double walled crater can be seen towards the top of the image. One theory is that it was once hot enough to be liquid. The surface cooled first, and when the interior froze it expanded, forcing the surface to crack.

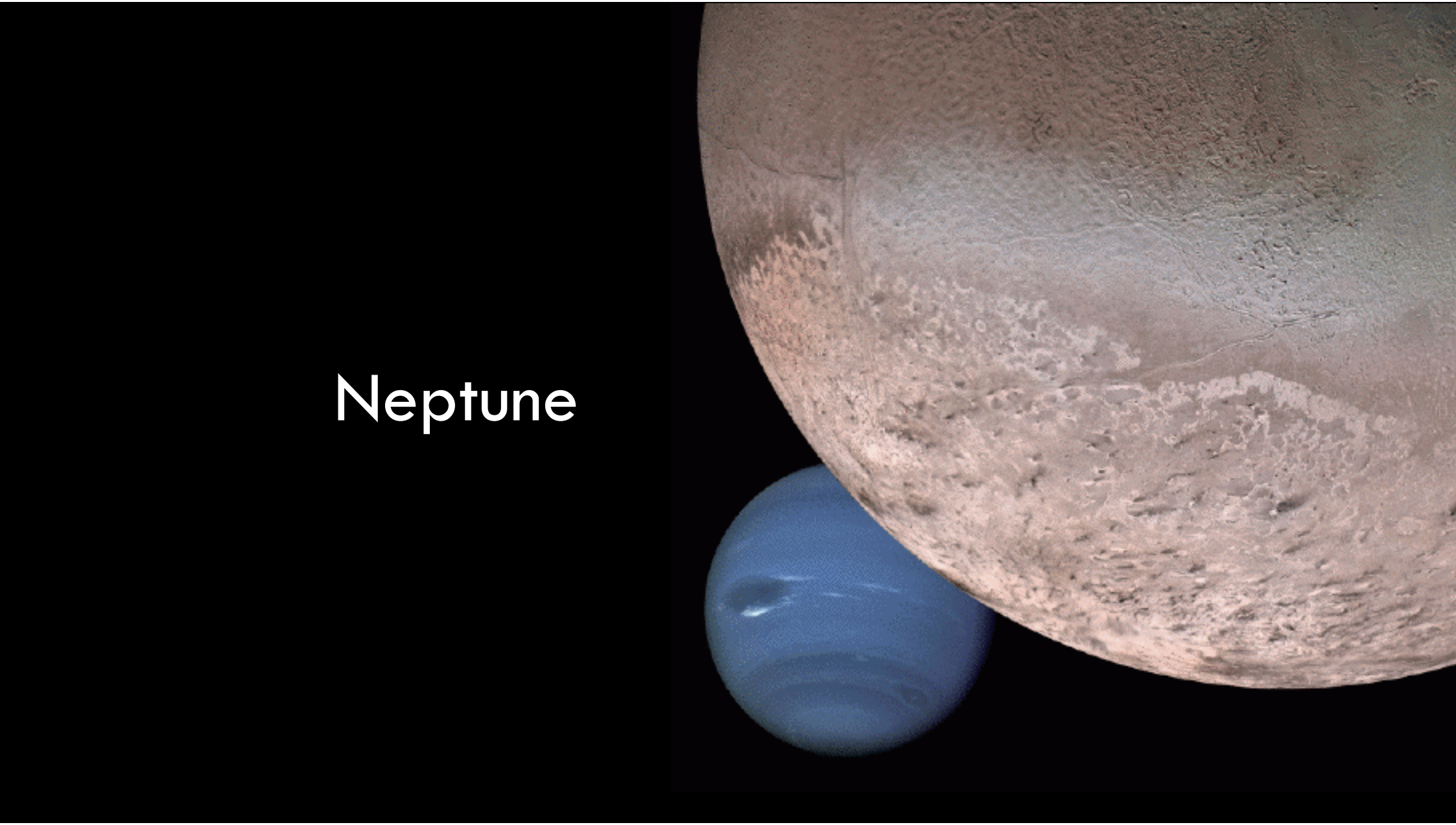
Oberon appears quite similar to Umbriel, though Oberon is 35% larger. Its surface is heavily cratered, showing more and larger craters than Ariel and Titania, some with bright rays of ejecta. Some of the crater floors are dark, perhaps covered with darker material that upwelled into the crater.

Large faults cut across the entire southern hemisphere, which indicates some geologic activity early in Oberon's history. The large crater is called Hamlet (200 km in diameter). The mountain on the limb rises 6 km above its surrounds.

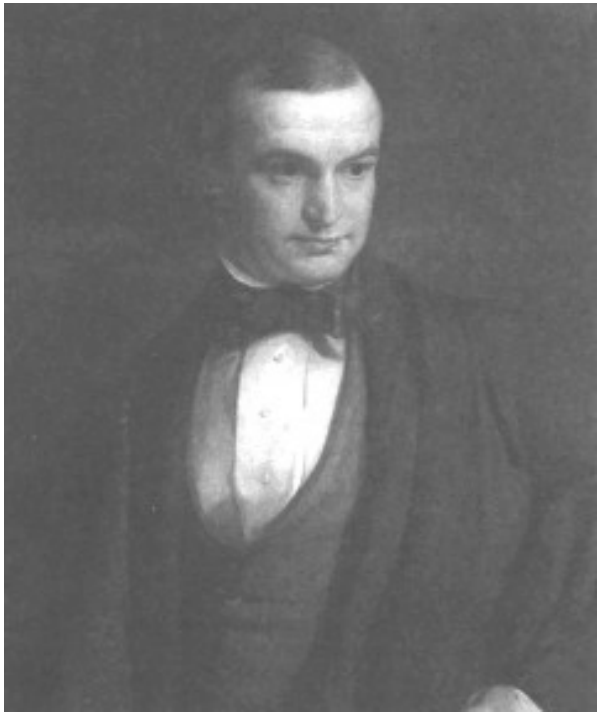
Of the ten small satellites which *Voyager* discovered, *Cordelia* and *Ophelia* appear to be the shepherding satellites for the bright Epsilon ring.

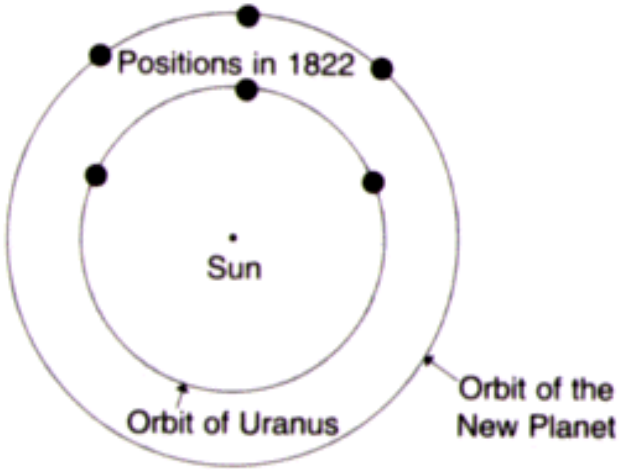


Neptune



Neptune was the first planet to be discovered due to a mathematical prediction. After Herschel's discovery, Uranus was not moving as predicted. Until 1822, it seemed to accelerate in its orbit, and to slow after that. Two young mathematicians independently set out to solve the mystery.

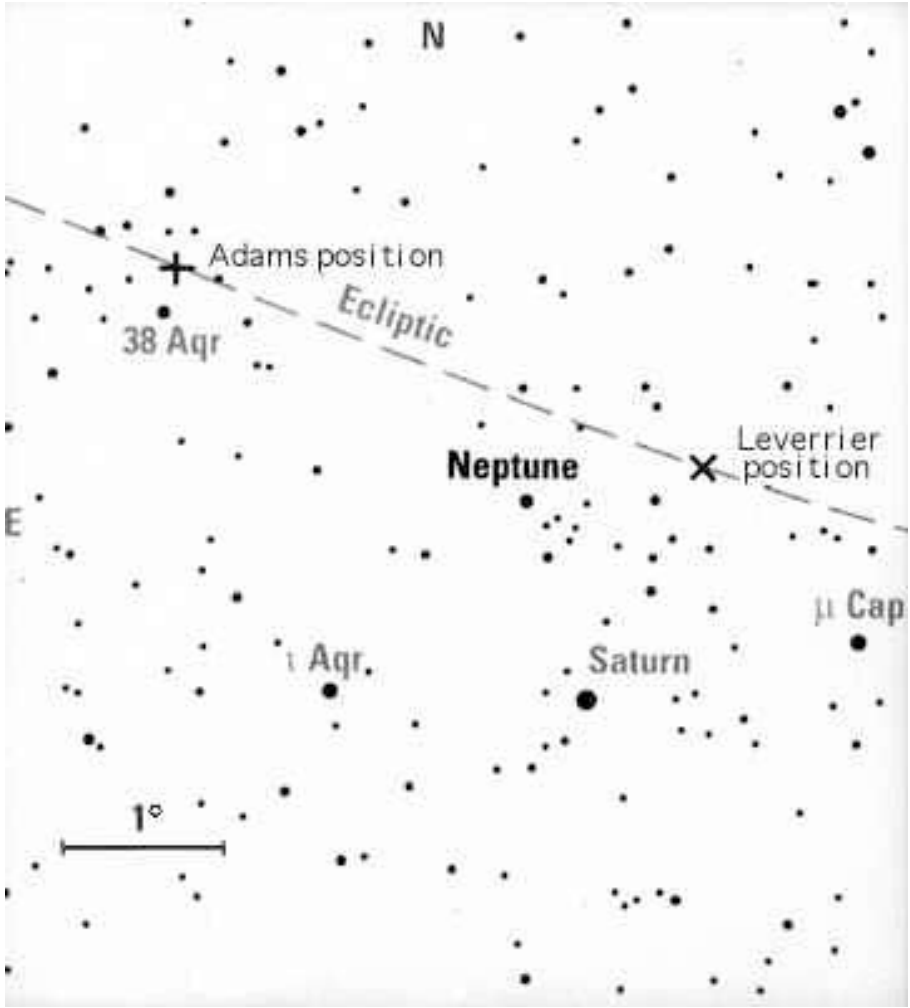




John Couch Adams predicted the position of the planet, as did Urbain Leverrier, whose solution led to the discovery of the planet by Johann Galle at the Berlin Observatory in 1846.

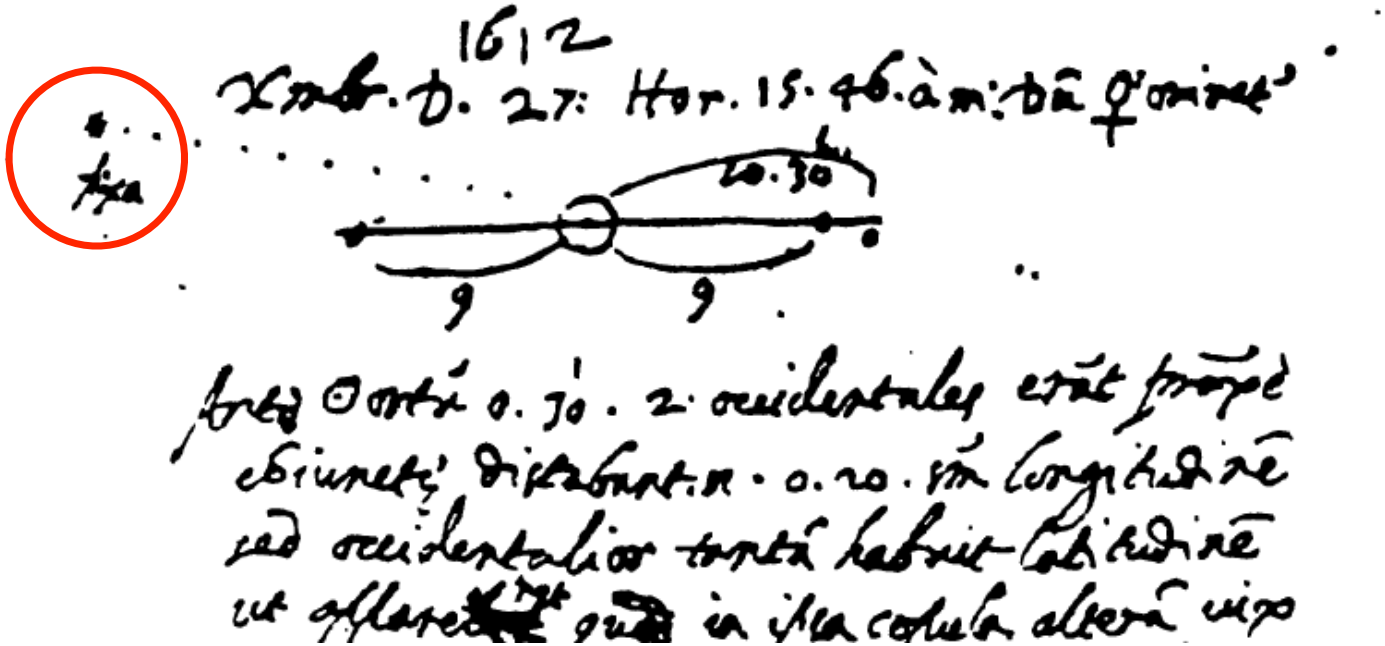
Neptune was discovered by Johann Galle in 1846, leading to an international dispute over priority.

On 12 July 2011, Neptune completed its first orbit since its discovery.



Comparison between Adams' and Leverrier's predicted positions for Neptune, and where it was found.

And in one of life's bizarre coincidences, it turns out that Galileo drew Neptune as a "fixed star" in one of his observations of Jupiter, 234 years before its official discovery in 1846!

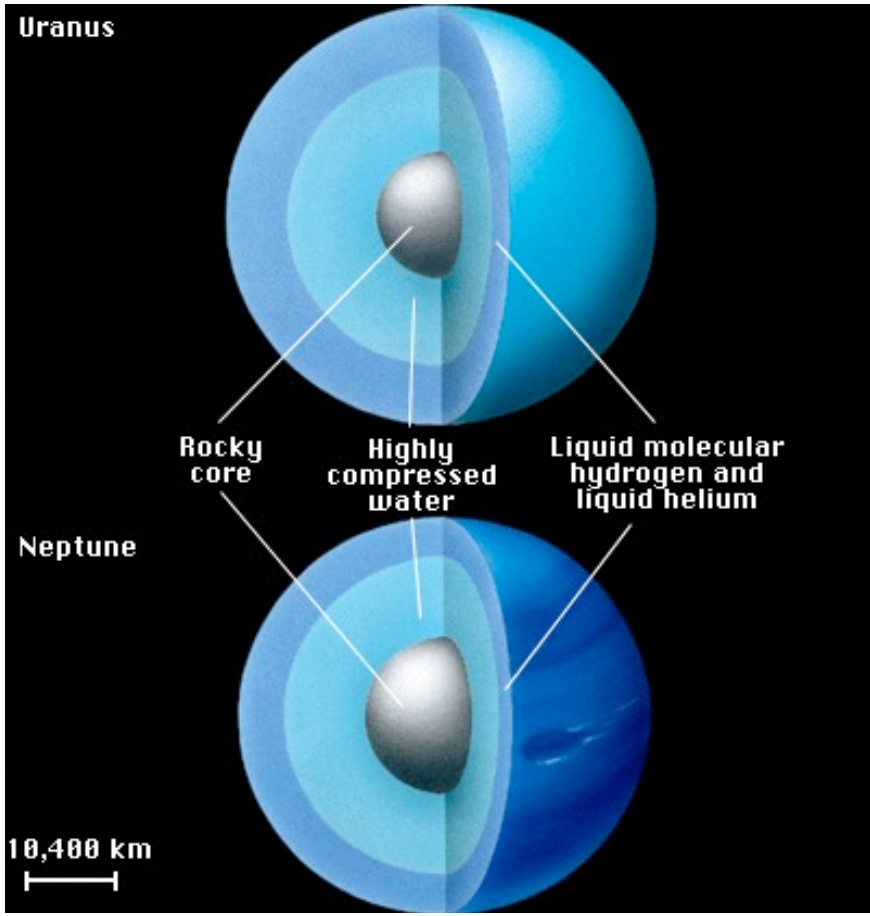


Galileo's notebook from 27th December 1612, showing Jupiter and its satellites, plus a "fixed star" which is actually Neptune (from Standish & Nobili, 1997)

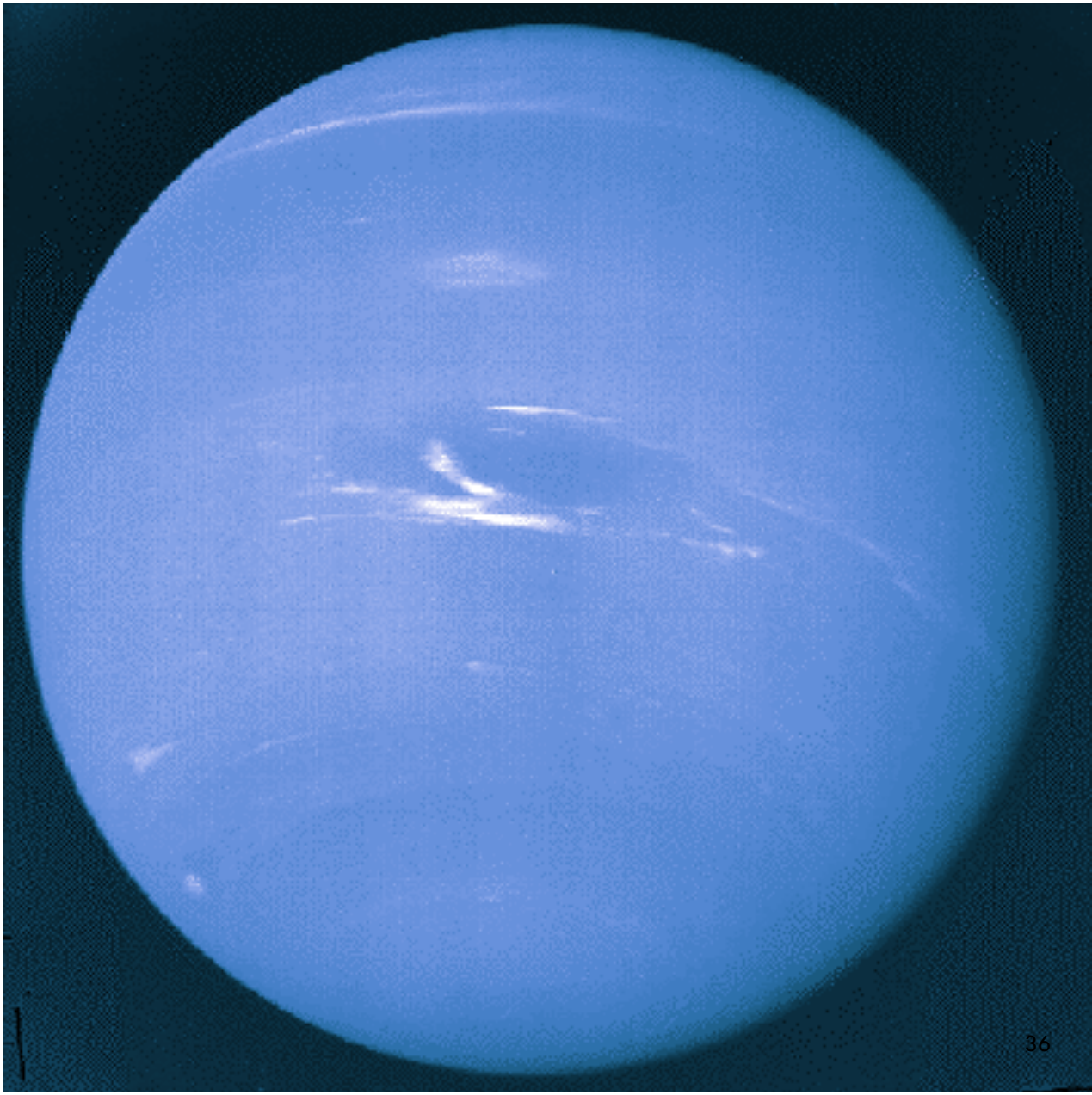
Basic data

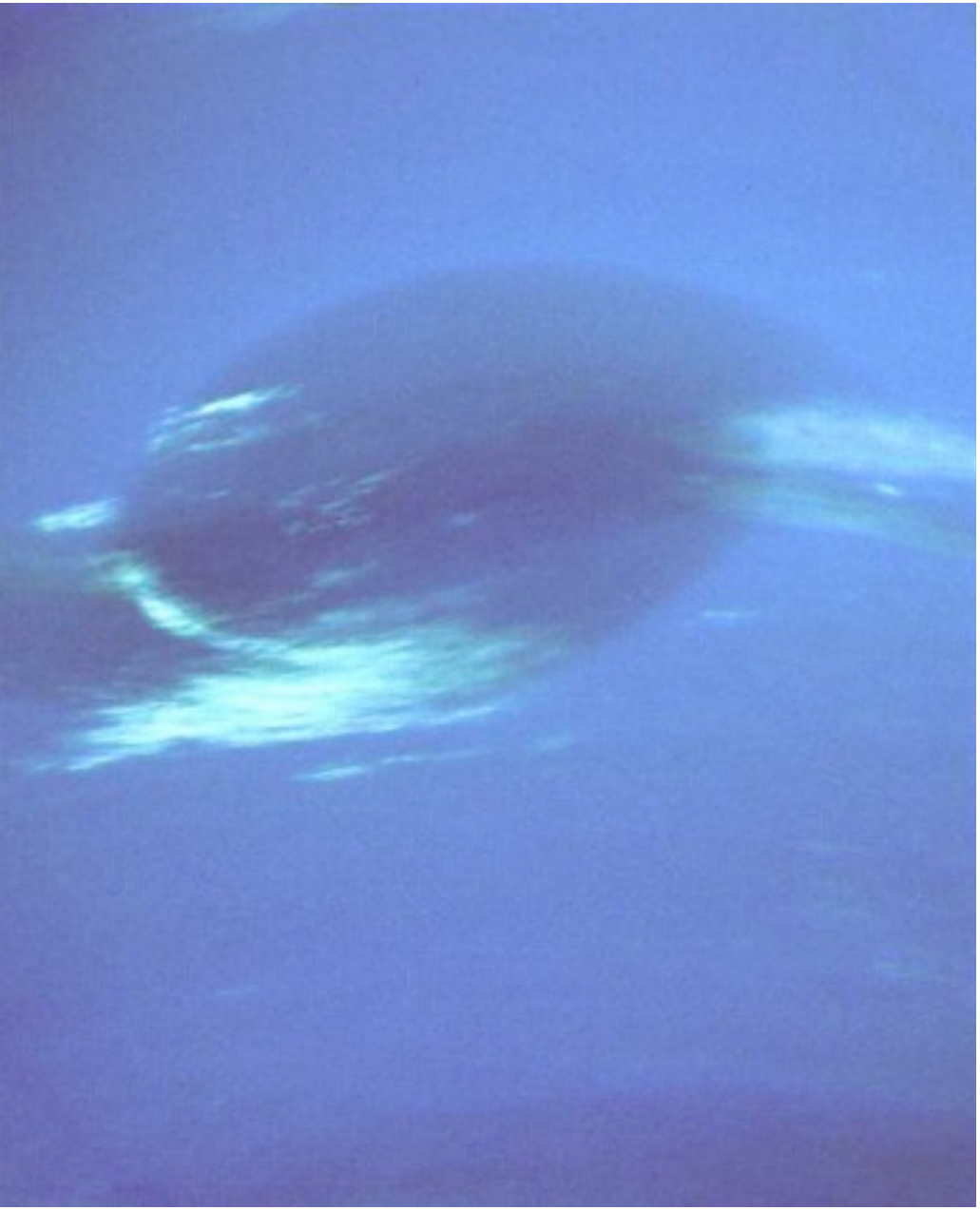
	Neptune	Neptune/Earth
Mass	102.43×10^{24} kg	17.147
Radius	24,764 km	3.883
Mean density	1.638 g/cm^3	0.297
Gravity (eq., 1 bar)	11.15 m/s^2	1.14
Semi-major axis	4495×10^6 km	30.047
Period	60 189 d	164.79
Orbital inclination	1.769°	-
Orbital eccentricity	0.0113	0.677
Axial tilt	28.3°	1.208
Rotation period	16.11 h	0.673

Neptune is almost a twin to Uranus. Almost identical in size, Neptune is slightly denser, and so slightly more massive than Uranus. Like Uranus, its atmosphere consists mostly of hydrogen and helium, with small amounts of other gases like methane. It is bluer than Uranus, with 3% methane in its atmosphere instead of 2% for Uranus.



Neptune's outer surface is far more interesting than Uranus'. Its upper atmosphere is cold enough for methane (and possibly nitrogen) to condense, which form high clouds. These show up vividly in photos and reveal the rapid winds and huge storms on the planet.

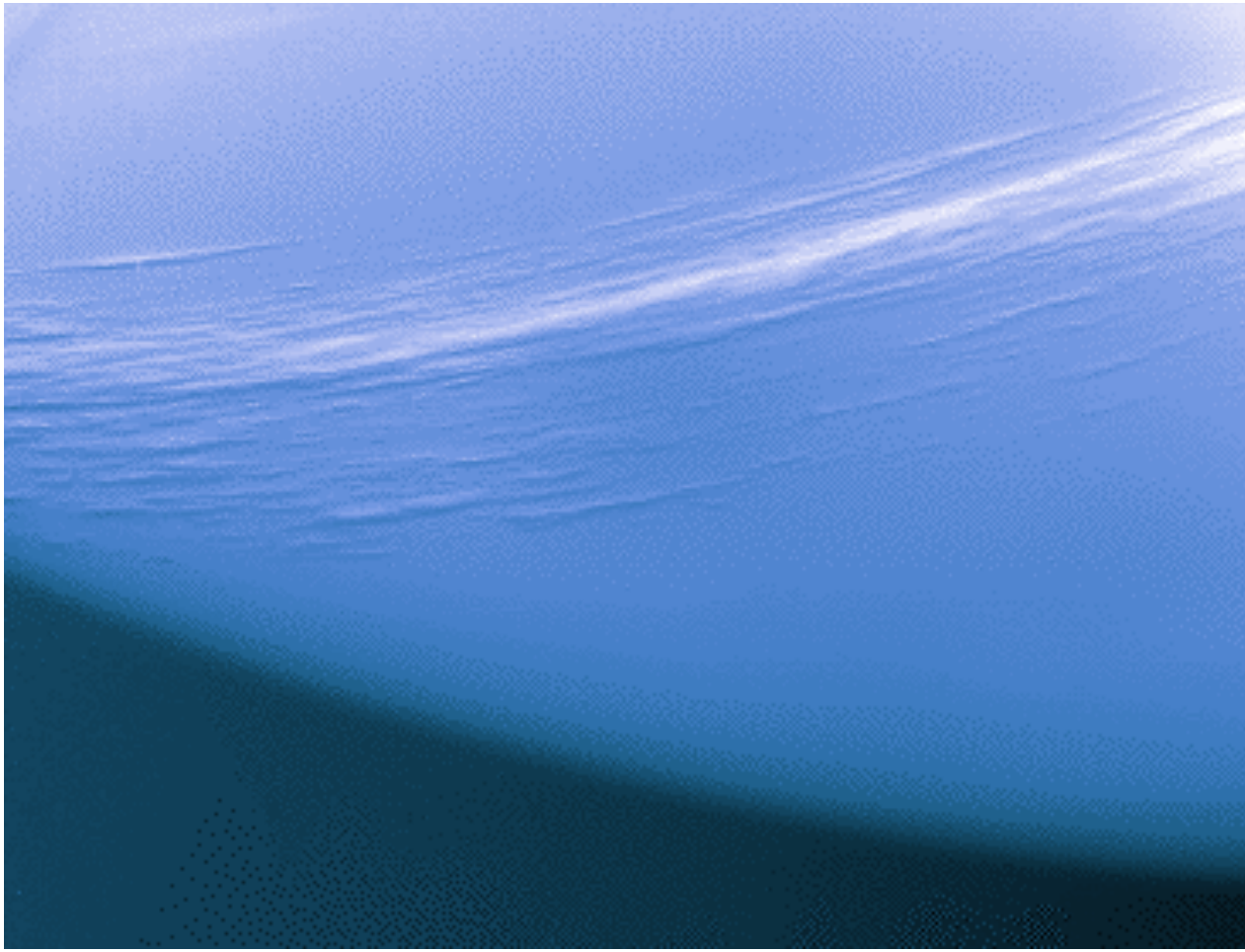




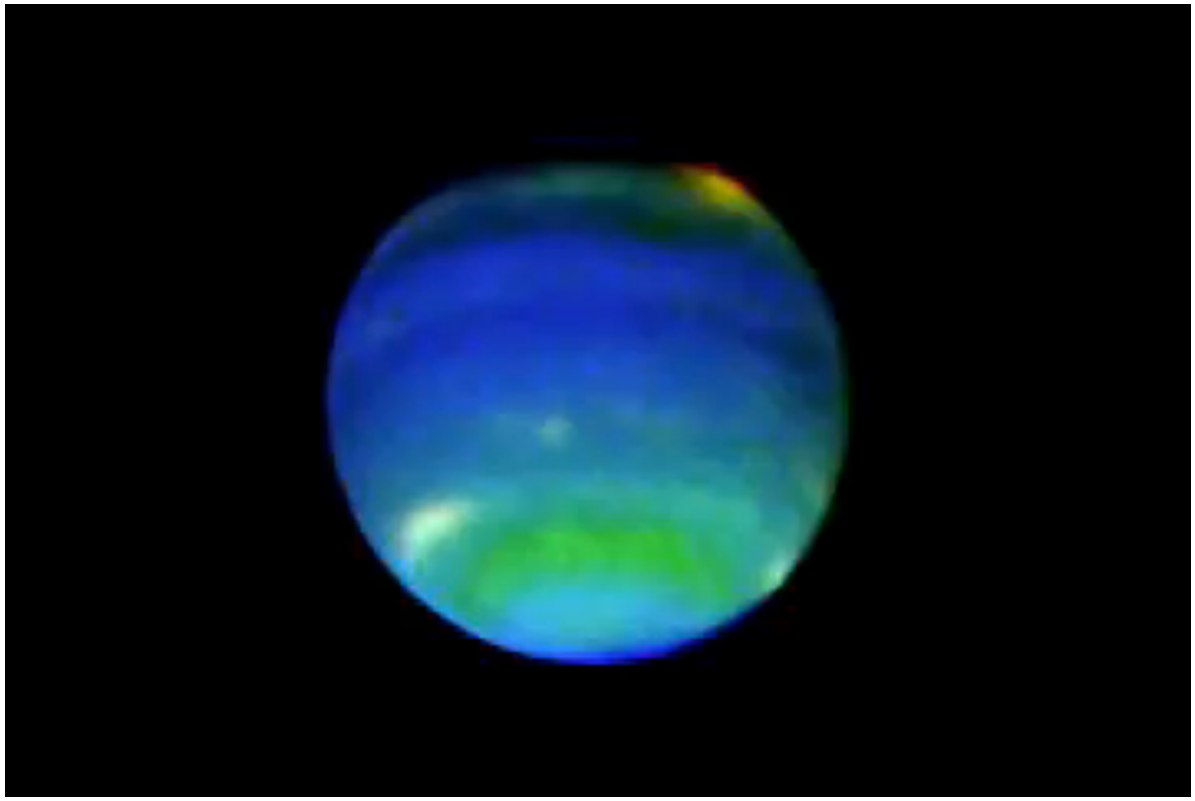
Voyager found a storm as large as the Earth, called the Great Dark Spot, about half the size of Jupiter's Great Red Spot. However, by the time *Hubble* imaged Neptune in 1994, the Dark Spot had vanished, so it was not nearly as long-lived as its Jovian cousin.

Long, bright clouds like cirrus were seen high in Neptune's atmosphere, casting shadows on the blue cloud deck 50 km below.

Neptune's winds are the fastest in the Solar System, reaching 2000 km/h. What drives these winds is not clear, given the relatively small amount of solar and internal heating to drive the circulation.

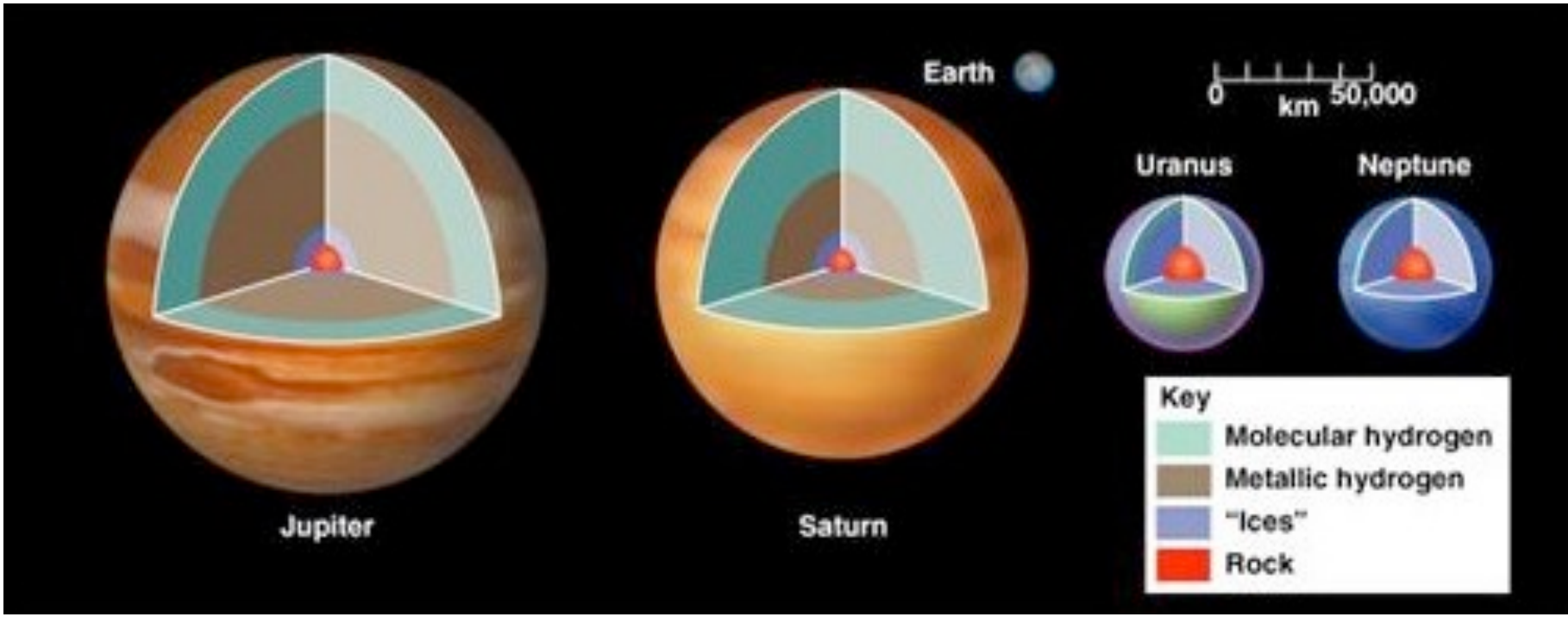


Here, images from HST over nine consecutive orbits have been assembled into a time-lapse movie showing a full 16-hour rotation of Neptune. These images show planet's powerful equatorial jet stream, immense storms, and dark spot in the Northern Hemisphere.

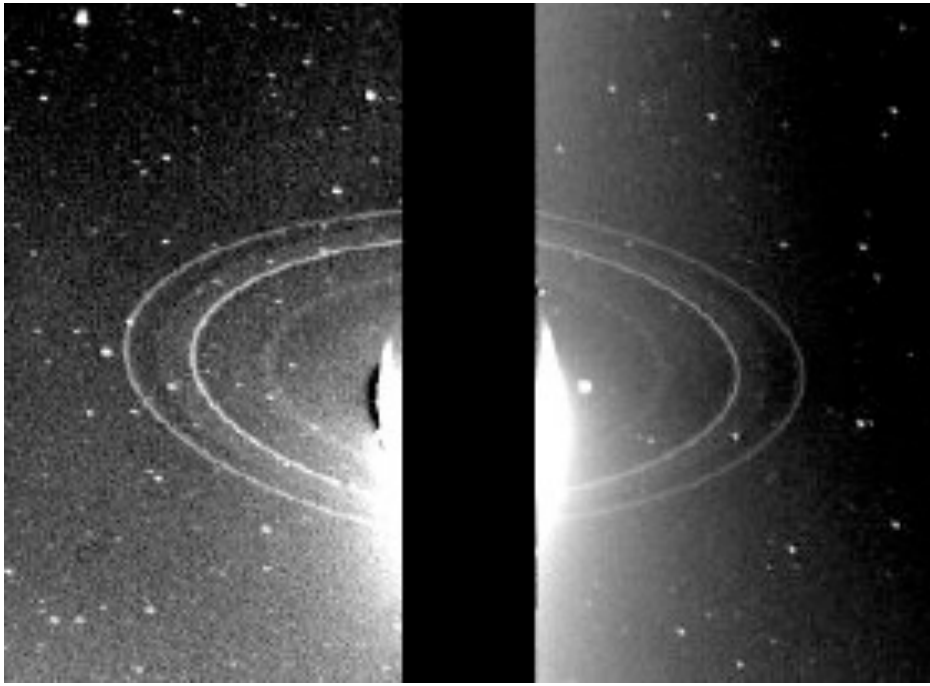


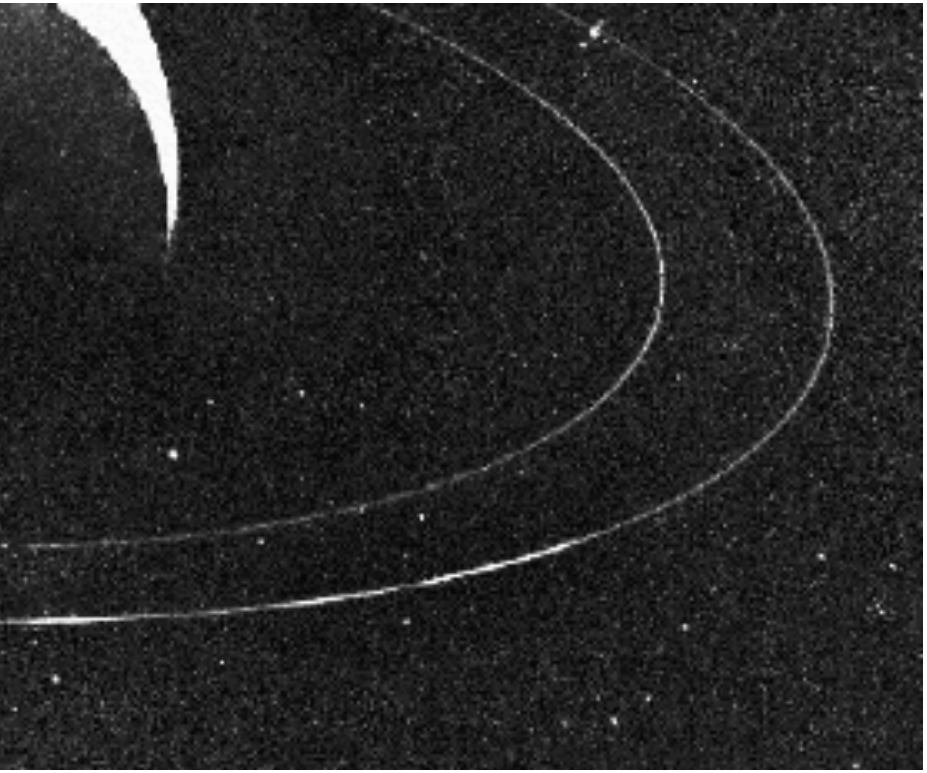
Neptune is also warmer than would be predicted just from the sunlight falling on it: the temperature of its outer atmosphere is 60 degrees Kelvin, whereas sunlight alone would produce 46 K. Heat must be flowing from its interior, as it does for Jupiter and Saturn. Uranus, however, does not have an internal heat source: why not?

Like Uranus, Neptune might better be called an “ice giant” than a “gas giant” like Jupiter and Saturn, which contain 80–90% hydrogen and helium by mass. Uranus and Neptune contain between 5 and 20% hydrogen and helium. Like Uranus, underneath this atmosphere is a thick layer of water, methane and ammonia ices, with a small rocky core about the size of Earth.



Neptune's rings are very faint and very dark. They contain large amounts of dust, and are probably rocky rather than icy.

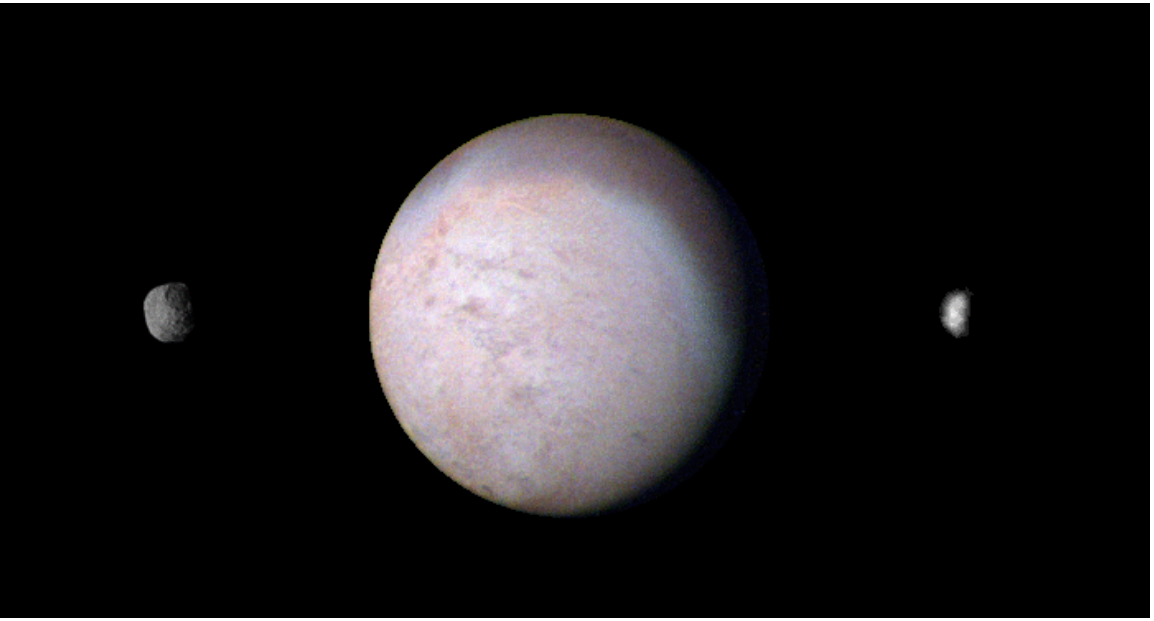




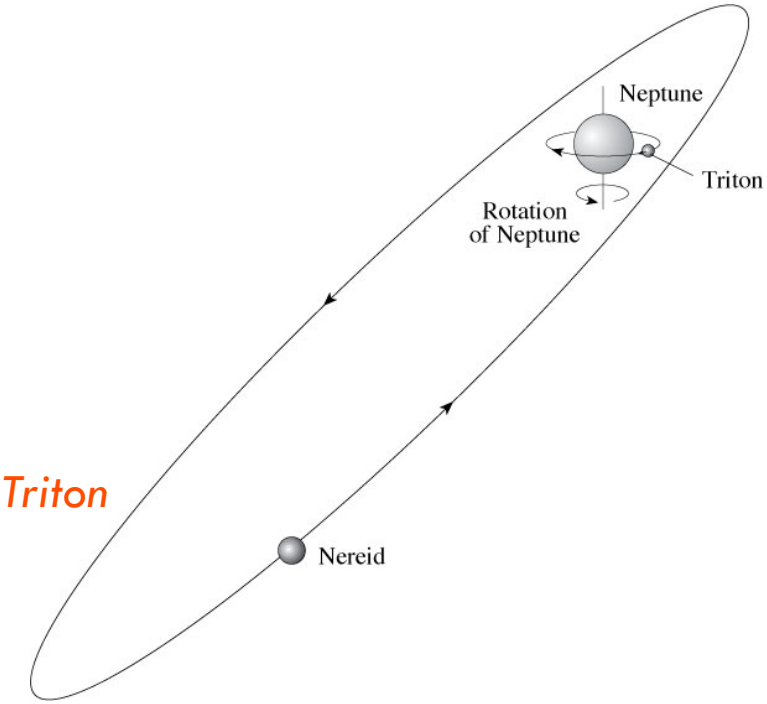
The rings are clumpy, with short arcs of denser material. These appear to be due to gravitational interaction with the small inner moon Galatea.

Neptune has thirteen moons, six discovered by *Voyager*. The two moons visible from Earth, *Triton* and *Nereid*, both have peculiar orbits. Nereid has a highly eccentric orbit, and Triton is unique among large planetary satellites because it orbits backwards – opposite to the sense of the planet's rotation. The six moons discovered by *Voyager* mostly orbit closer to Neptune than the rings.

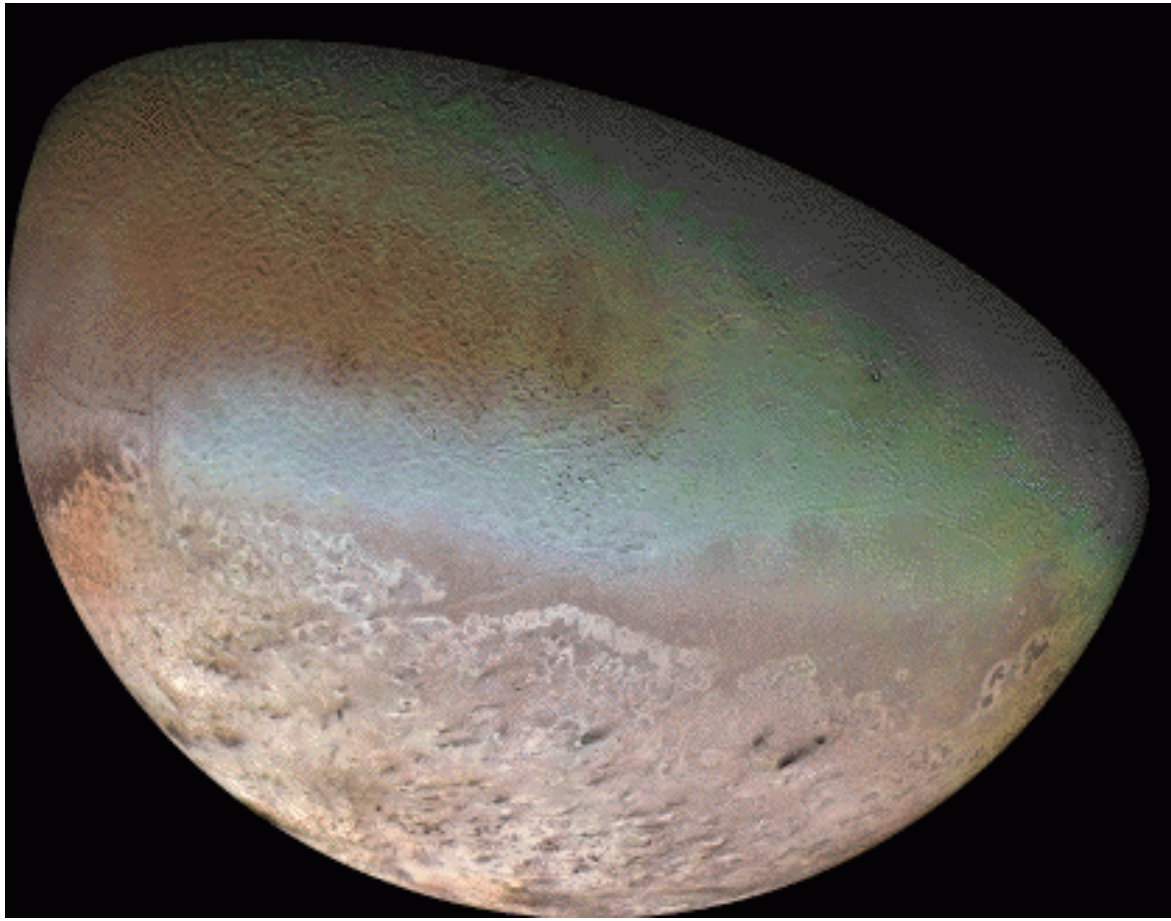
The three major Neptunian satellites: Proteus, Triton, and Nereid.

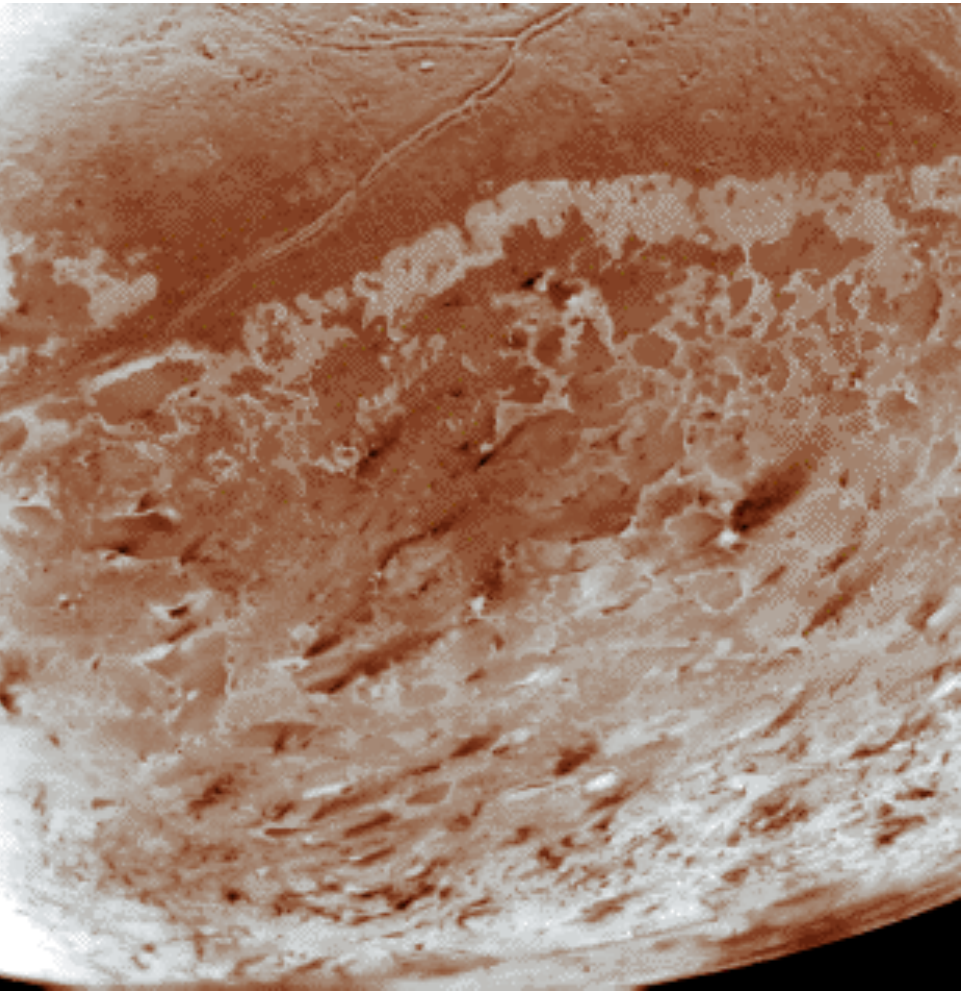


The orbits of Triton and Nereid



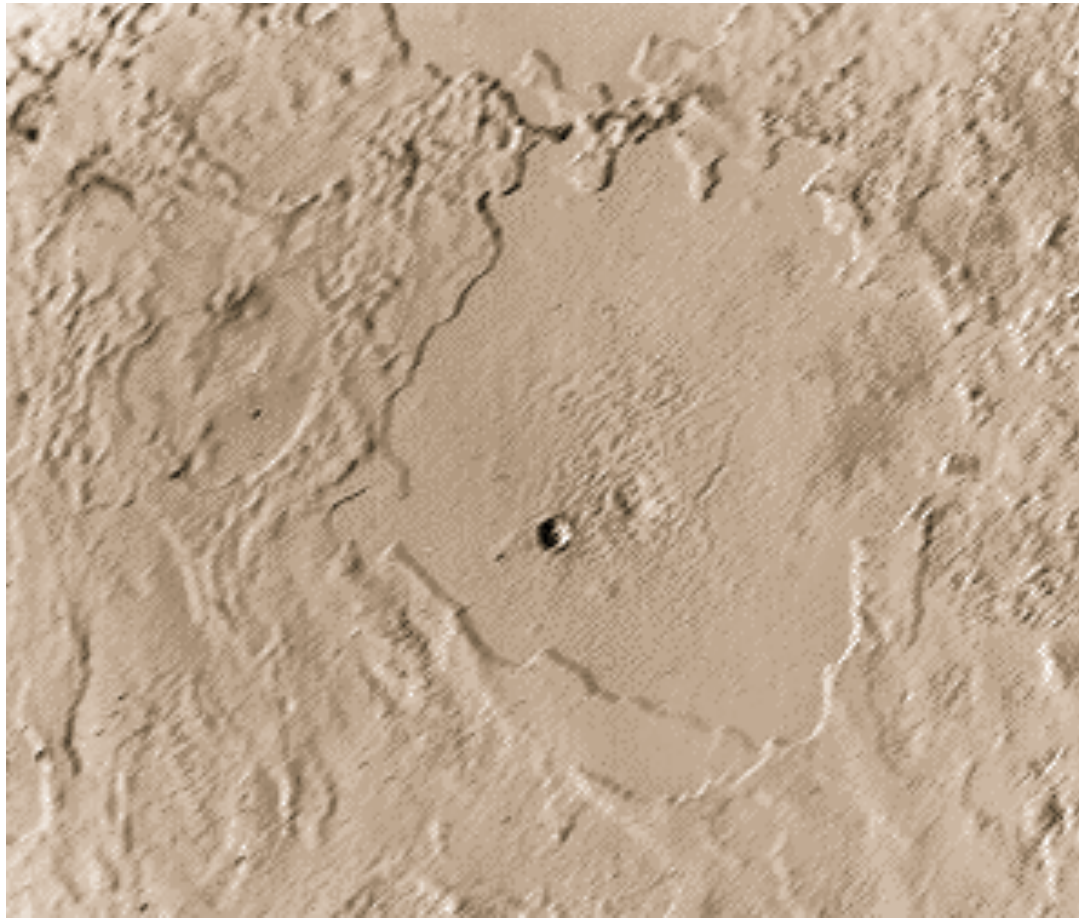
Triton is by far the largest of Neptune's satellites (diameter 2700 km, just 12% smaller than Earth's moon). It is very bright, with an albedo of 70%, which is due to a coating of frozen nitrogen. The surface temperature is –235° C, the coldest temperature yet measured in the Solar System. Triton has a density of about 2.1 g/cc^3, which means means it must be about 2/3 rock, much more than the icy satellites of Saturn and Uranus.

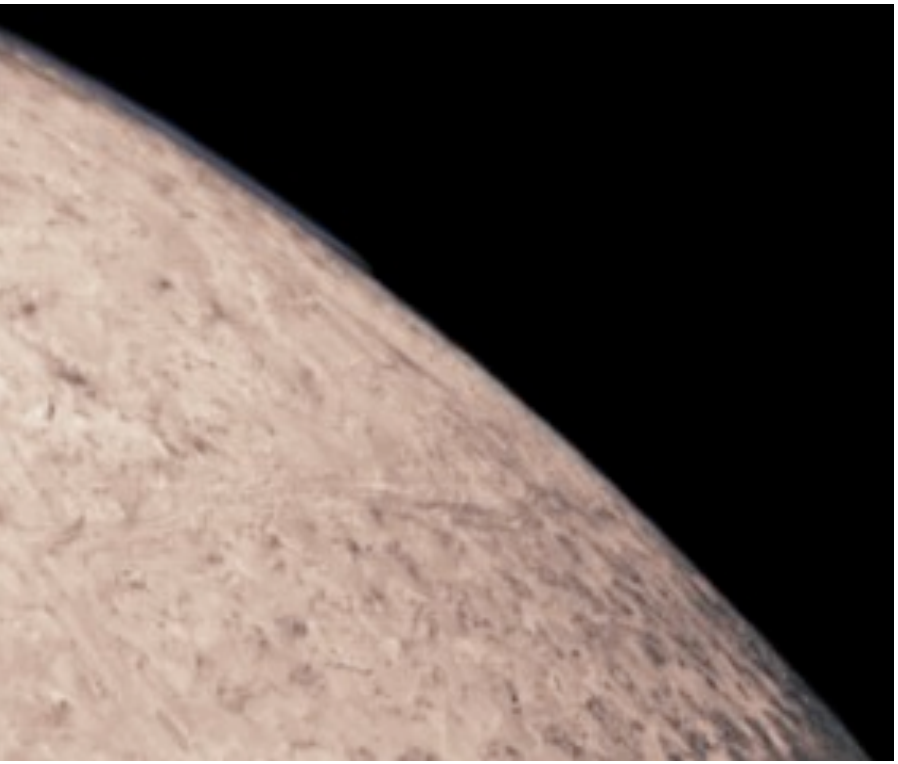




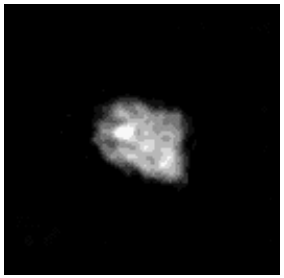
Voyager took this picture of Triton's south pole, revealing evidence of ice volcanoes. The dark streaks are material spread downwind from recent volcanic eruptions. The favoured mechanism for the volcanoes is that the Sun heats darkened methane ice on the surface, which heats underlying nitrogen ice that vents through the surface as volcanoes. The fact that the streaks all point in the same direction suggest that the very thin atmosphere is able to blow material across the surface, and that there is a prevailing wind direction.

The surface shows a jumbled terrain, including smooth icy expanses filling what appear to be old impact basins. The few impact craters suggest a young surface.



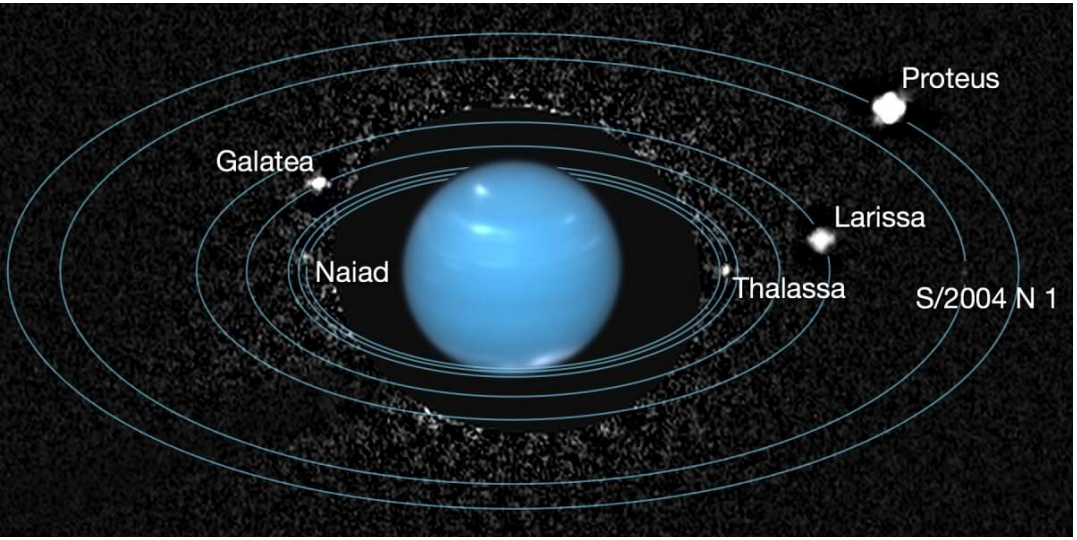


Voyager photographed a thin layer of cloud along the limb of the moon, probably of nitrogen crystals.



Nereid is about 340 kilometres in diameter and takes 360 days to make one orbit. Nereid's orbit is the most eccentric in the solar system (eccentricity 0.75). Its distance to Neptune ranges from about 1.3 million kilometres to 9.6 million kilometres.

Six moons were discovered by *Voyager*, and five more have since discovered from the ground. The six Voyager moons are mostly closer to Neptune than the rings, and are considered regular, since they orbits in the equatorial plane in the same direction as Neptune.

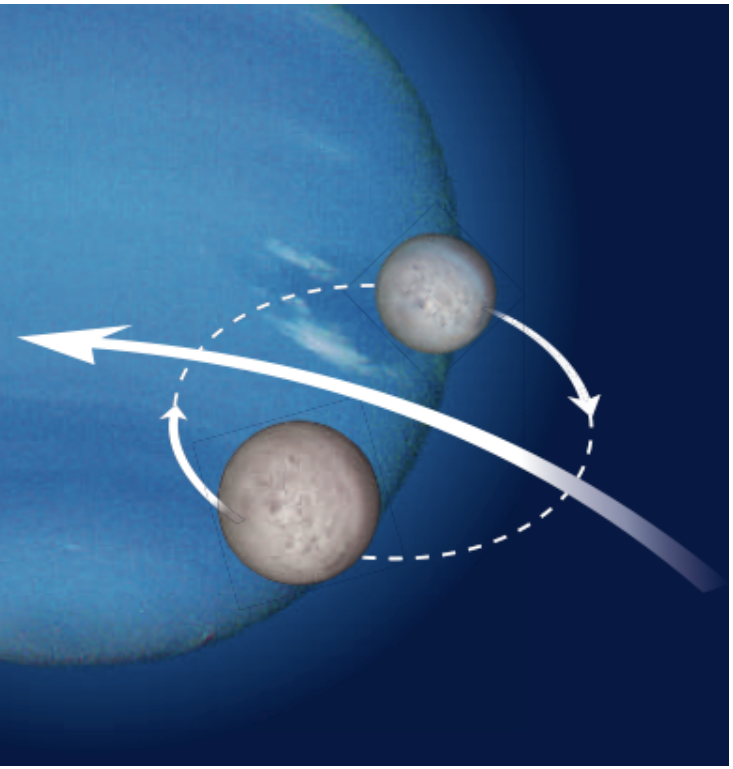


It is likely that Triton formed in the Kuiper belt and was captured when it ventured too close to Neptune. One suggestion is that Neptune originally had its own more normal family of moons. Triton collided with a small icy moon, with a mass a few percent of Triton's. The collision completely destroyed the original moon, and robbed Triton of enough energy that it was captured into an eccentric, retrograde orbit around Neptune. As its orbit circularised, the remaining satellites were destroyed or ejected, all except Nereid, which was left in an eccentric, inclined orbit.

Artist's impression of moons colliding

This theory, however, has problems, mostly because Triton's large mass make capture difficult.

In an extra twist, recent work suggests that Triton was originally part of a binary, similar to Pluto-Charon, which strayed too close to Neptune.



During the interaction, as the binary was ripped apart, one object was moving more slowly relative to Neptune and so could be captured into a bound orbit relatively gently.

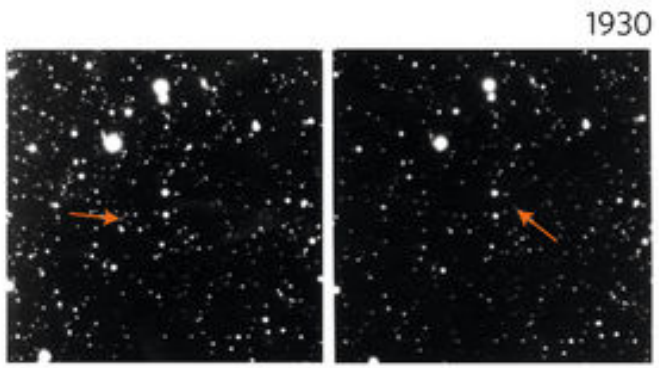
Pluto and Charon

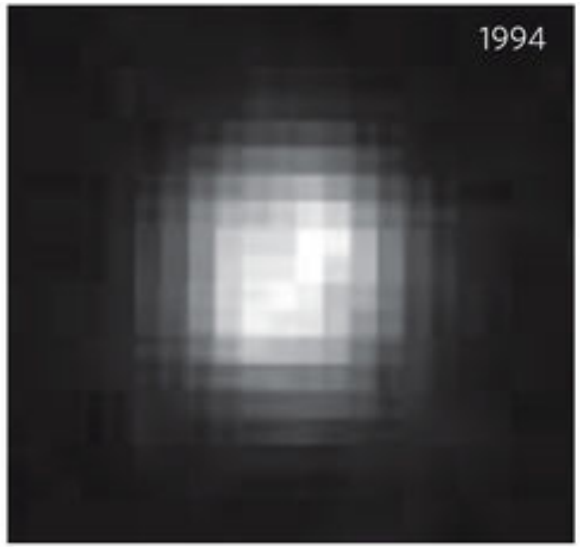
Pluto and Charon form an enigmatic double at the outer edge of the Solar System. They orbit each other once a week, in a highly eccentric orbit around the Sun which is tilted well out of the plane of the ecliptic. The combined mass of Pluto and Charon is less than one percent of Earth's. Pluto is now recognised as one of the largest members of the Kuiper belt.

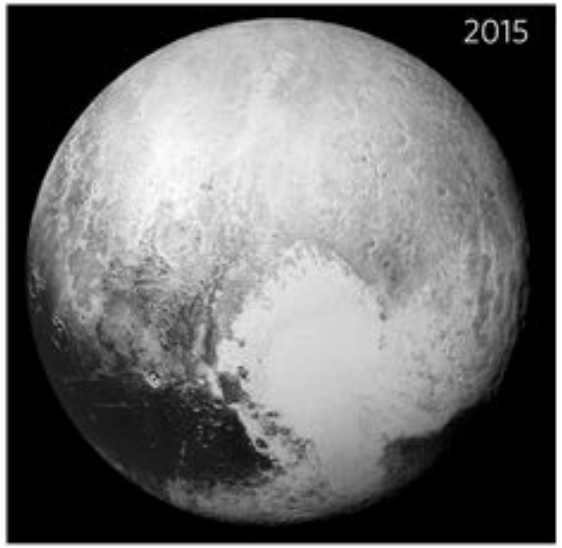
Before *New Horizons*' visit in 2015, very little was known about the pair.

HST image of Pluto and Charon taken in 1994

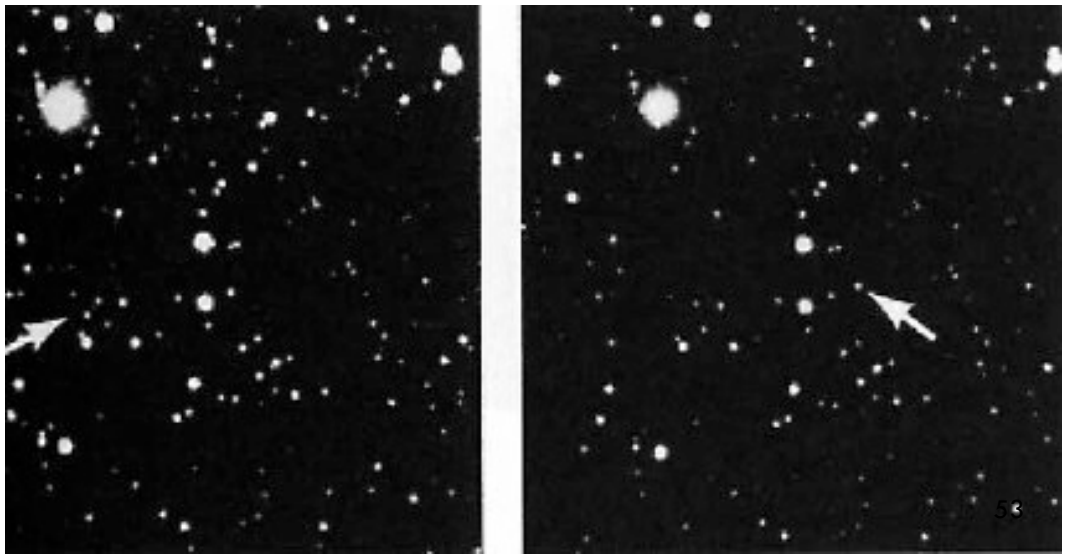
How far we've come…







Pluto was discovered because of irregularities in Neptune's motion. Two different predictions had suggested the existence of a planet beyond Neptune, called Planet O (William Pickering) and Planet X (Percival Lowell). On February 19, 1930, Clyde Tombaugh at the Lowell Observatory found a faint, star-like image which was moving. Ironically, both calculations were wrong! but he found the planet anyway.



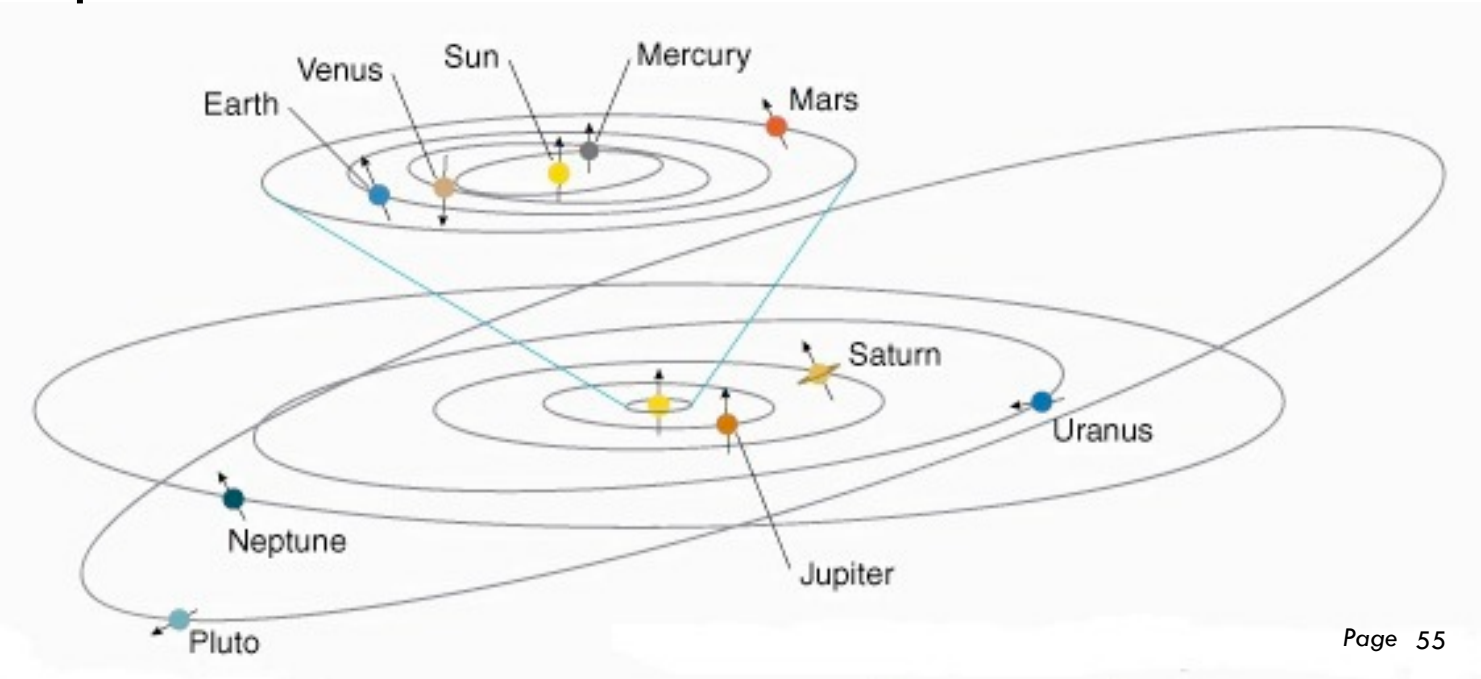
The discovery images for Pluto, showing the star moving between the two exposures, taken two weeks apart.

Basic data

	Pluto/Charon		Pluto/Charon / Earth	
Mass	0.01303 x 10^{24} kg	0.00159 x 10^{24} kg	0.0025	0.00032
Radius	1187 km	606 km	0.186	0.093
Mean density	1.86 g/cm^3	1.70 g/cm^3	0.380	0.335
Semi-major axis	5906 x 10^6 km		39.48	
Period	90 560 d		247.9	
Orbital inclination	17.16°		-	
Orbital eccentricity	0.2488		14.6	
Tilt of axis	122.53°		5.3	
Surface gravity	0.62 m/s^2		0.071	
Rotation period	–153.2928 h		6.41	
Length of day	153.2820 h		6.39	

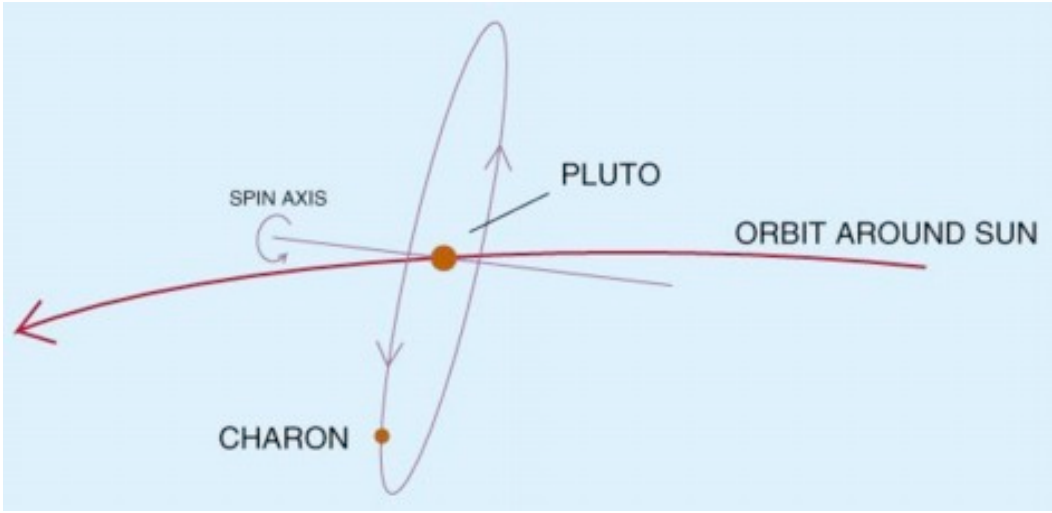
Pluto's highly elongated orbit takes it from 29.7 AU (within the orbit of Neptune) to 49.3 AU. It crossed back outside Neptune's orbit in March 1999, and will be further away than Neptune until 2227.

Pluto's orbit is also inclined by 17° to the plane of the ecliptic. Pluto is locked in a 3:2 resonance with Neptune, so its orbital period is exactly 1.5 times longer than Neptune's.



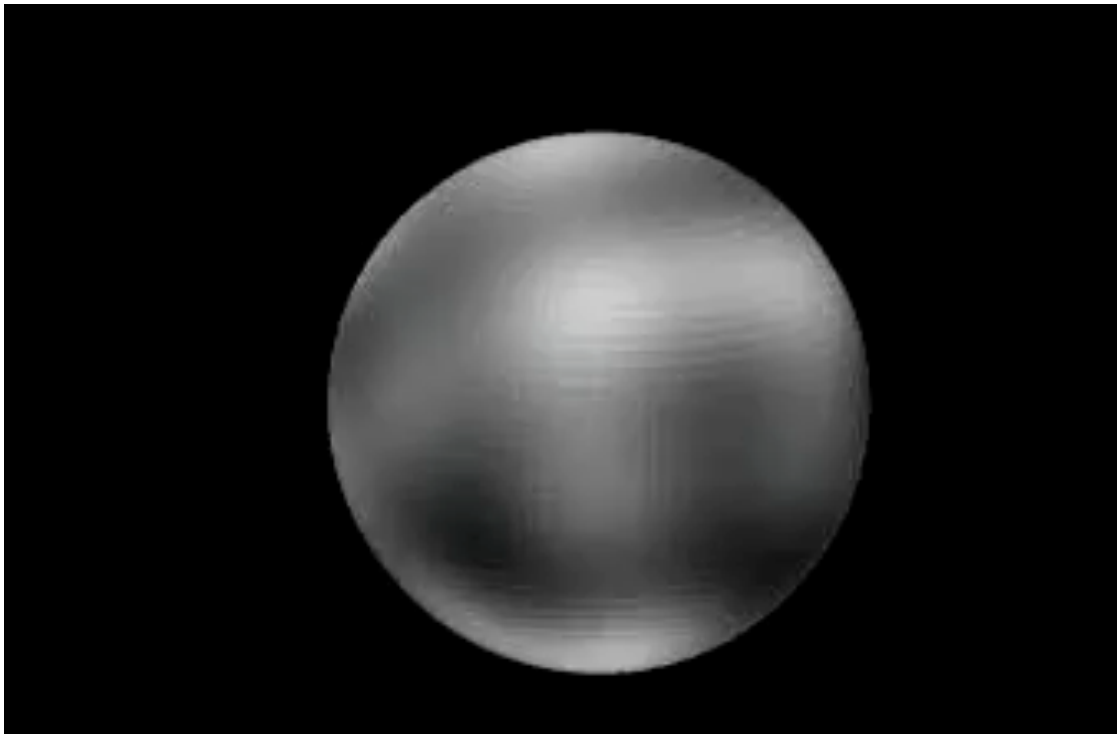
In 1978, Pluto was found to have a satellite with an orbital period of 6.4 days, which was named *Charon*. Like Neptune, Pluto orbits on its side, and Charon orbits in its equatorial plane. By good fortune, Charon was discovered just before its orbital plane became edge-on to us, so from 1985 to 1990 Charon passed in front and behind Pluto every 6.4 days. It will be 124 years before this happens again.

Charon is the largest moon relative to its planet. The mass ratio is large enough that the centre of mass is outside the body of Pluto, so Pluto and Charon are sometimes referred to as a double dwarf planet system.



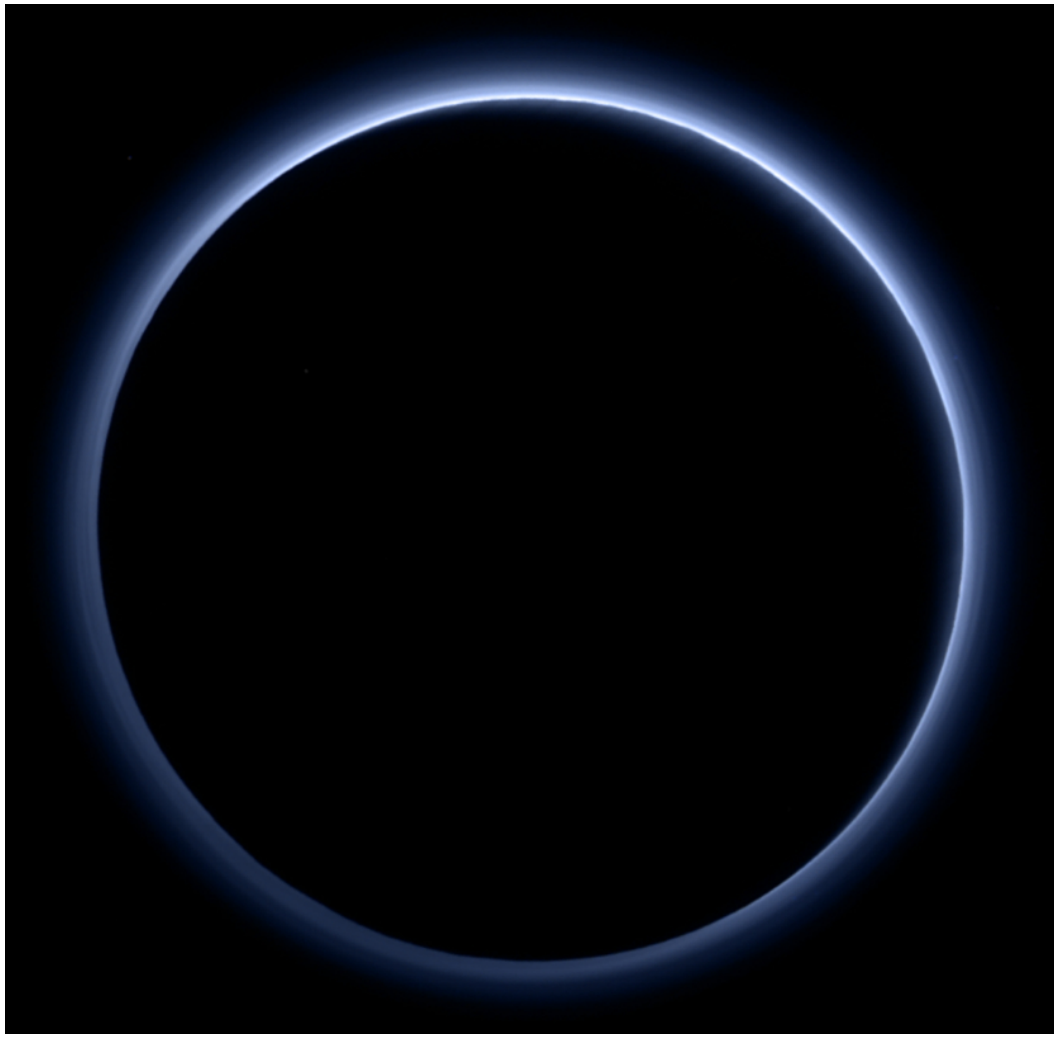
Charon is over half the size of Pluto, but both are much smaller than the Earth.

Prior to *New Horizons*, the best images of Pluto were taken using the *Hubble Space Telescope*, which can just barely see contrast on its surface. The animation shows snapshots of nearly the entire surface of Pluto, taken as the planet rotated through a 6.4-day period. Pluto shows more large-scale contrast than any planet, except Earth (second only to Iapetus).



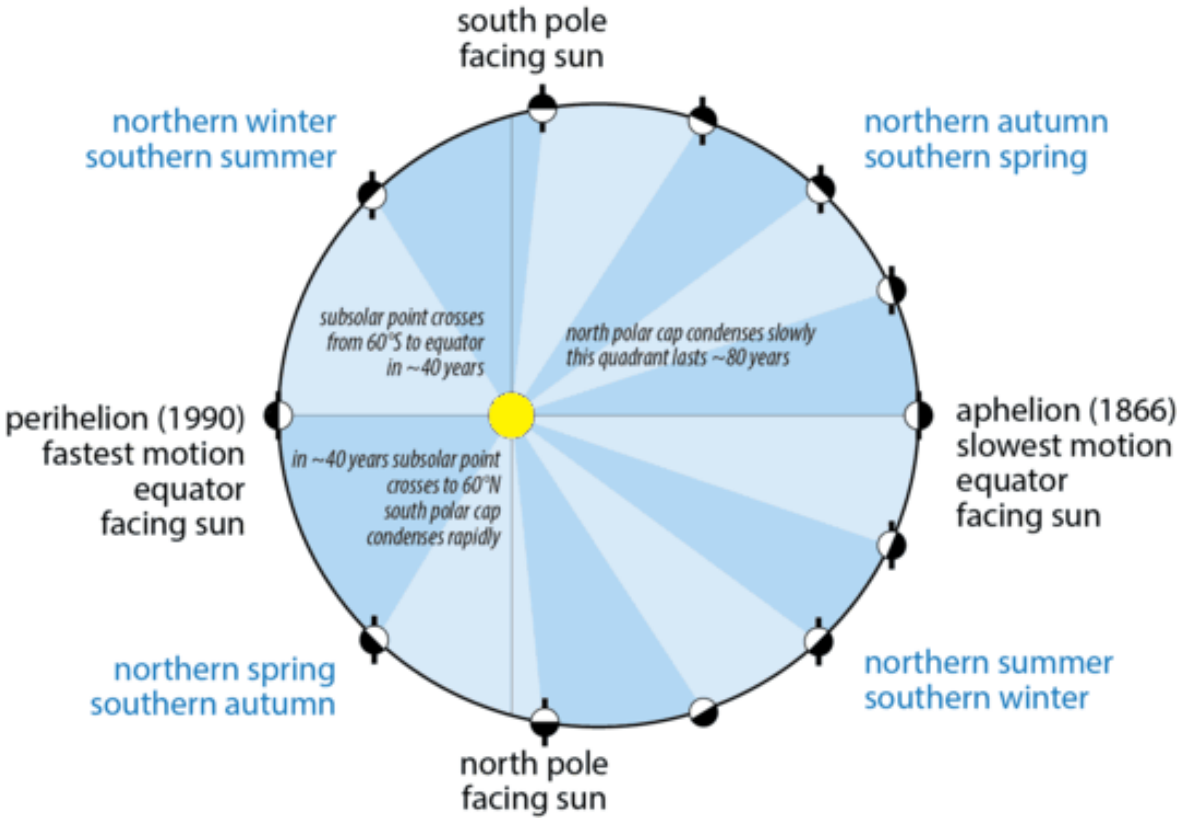
Pluto is slightly denser than Charon, by about 9%, so both consist of a mix of rock and ice. The surface temperature on Pluto varies between about –235° and –210° C (38 to 63 K).

Pluto has a tenuous atmosphere, consisting mostly of nitrogen, with trace amounts of methane.



Departure shot of Pluto by New Horizons, showing Pluto's atmosphere backlit by the Sun

Like Uranus, Pluto has extreme seasons because of its orbital tilt. Pluto's south pole is just entering its arctic night after half a Pluto year (124 Earth years!) of constant illumination.

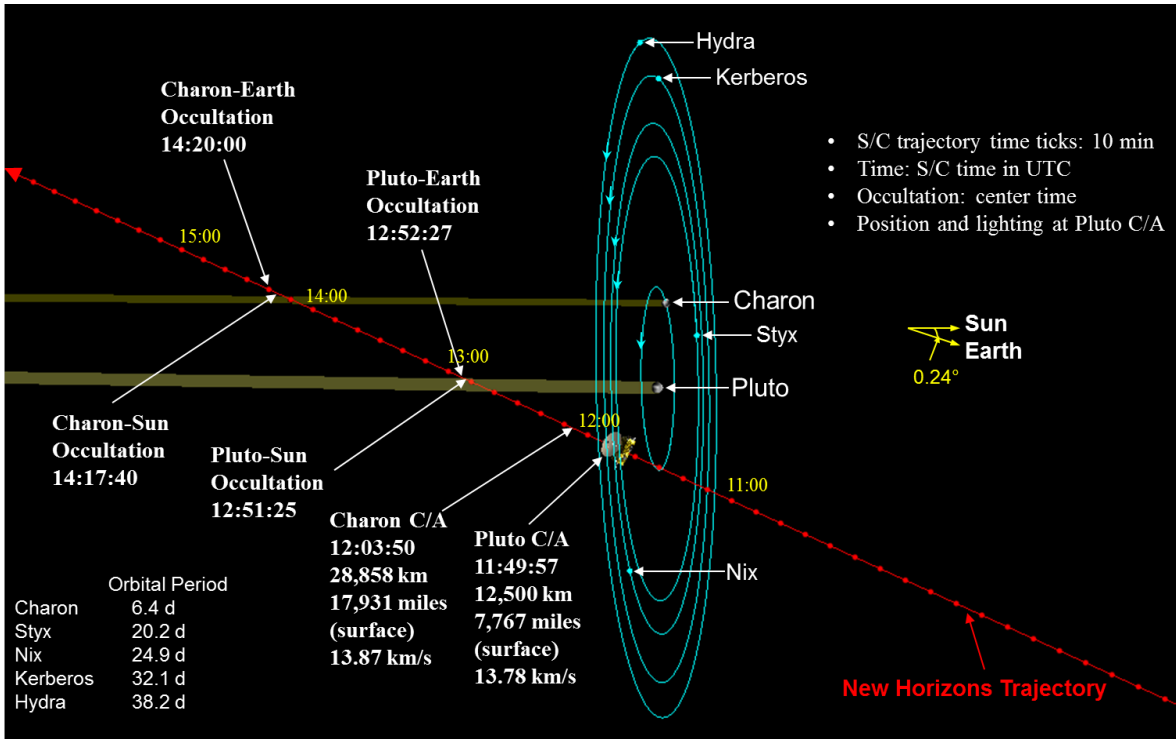


Pluto and Charon are both tidally locked, so they always present the same face to each other. From one side of Pluto, Charon would stay in the same place in the sky as the stars rotated past, while from the far side you would never see Charon at all.

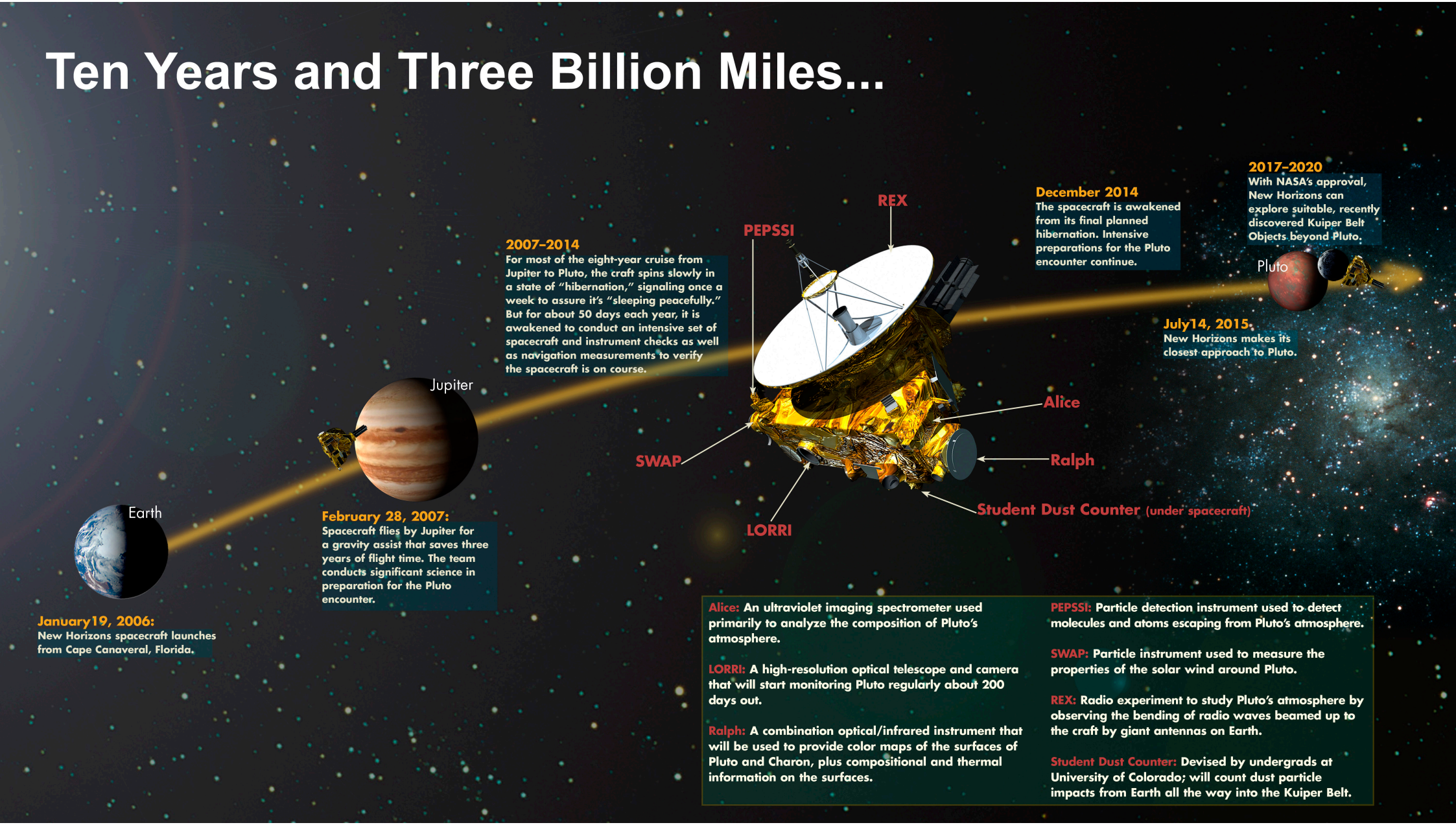
Artist's impression of the dwarf planet Pluto as it might appear from the surface of Charon. (Image by Mark Garlick)

The *New Horizons* flyby

On 14 July 2015, the New Horizons spacecraft flew past Pluto and Charon, after nearly ten years in space. It flew within 12,500 km of Pluto's surface, and 27,000 km of Charon's surface. It also passed through the shadow of both objects, in order to try to detect an atmosphere.



Ten Years and Three Billion Miles...



January19, 2006:
New Horizons spacecraft launches from Cape Canaveral, Florida.

February 28, 2007:
Spacecraft flies by Jupiter for a gravity assist that saves three years of flight time. The team conducts significant science in preparation for the Pluto encounter.

2007–2014
For most of the eight-year cruise from Jupiter to Pluto, the craft spins slowly in a state of "hibernation," signaling once a week to assure it's "sleeping peacefully." But for about 50 days each year, it is awakened to conduct an intensive set of spacecraft and instrument checks as well as navigation measurements to verify the spacecraft is on course.

December 2014
The spacecraft is awakened from its final planned hibernation. Intensive preparations for the Pluto encounter continue.

July14, 2015.
New Horizons makes its closest approach to Pluto.

2017–2020
With NASA's approval, New Horizons can explore suitable, recently discovered Kuiper Belt Objects beyond Pluto.

Alice: An ultraviolet imaging spectrometer used primarily to analyze the composition of Pluto's atmosphere.

LORRI: A high-resolution optical telescope and camera that will start monitoring Pluto regularly about 200 days out.

Ralph: A combination optical/infrared instrument that will be used to provide color maps of the surfaces of Pluto and Charon, plus compositional and thermal information on the surfaces.

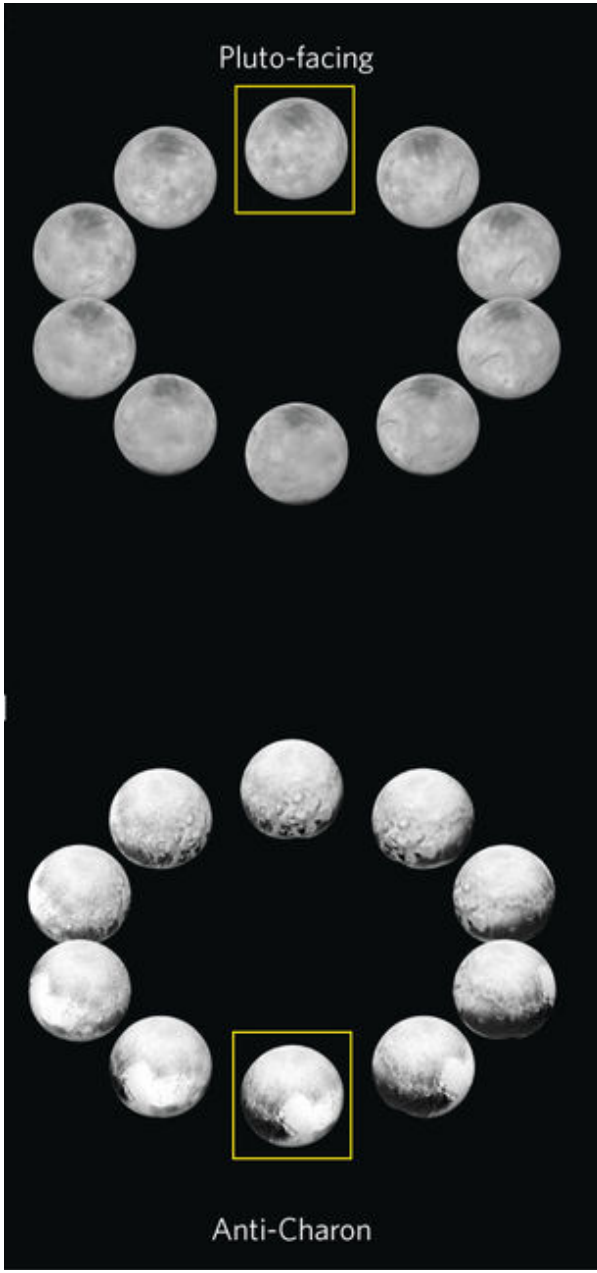
PEPSSI: Particle detection instrument used to detect molecules and atoms escaping from Pluto's atmosphere.

SWAP: Particle instrument used to measure the properties of the solar wind around Pluto.

REX: Radio experiment to study Pluto's atmosphere by observing the bending of radio waves beamed up to the craft by giant antennas on Earth.

Student Dust Counter: Devised by undergrads at University of Colorado; will count dust particle impacts from Earth all the way into the Kuiper Belt.

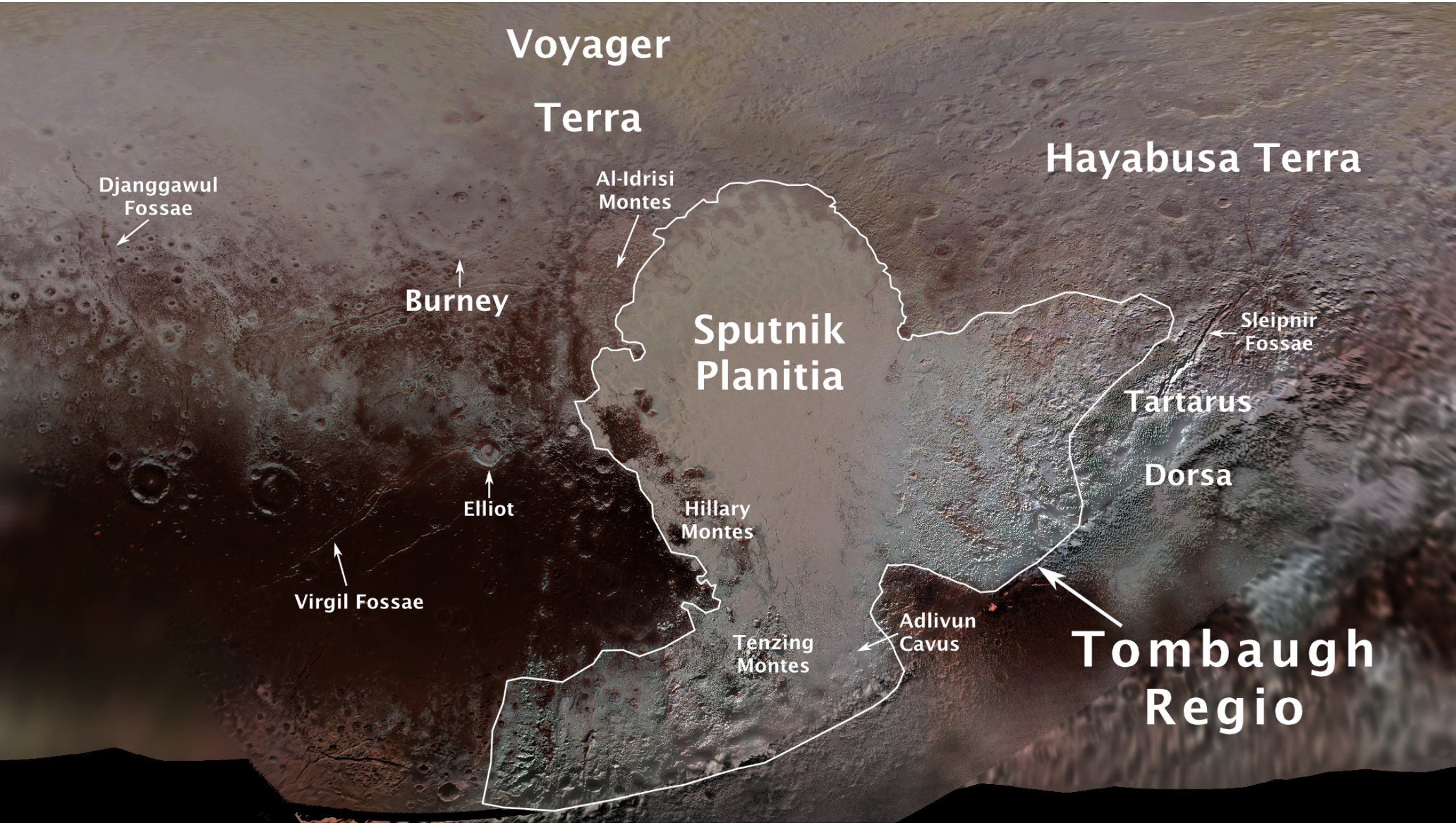
At closest approach, *New Horizons* could see the side of Pluto that faces away from Charon, and the Pluto-facing hemisphere of Charon.



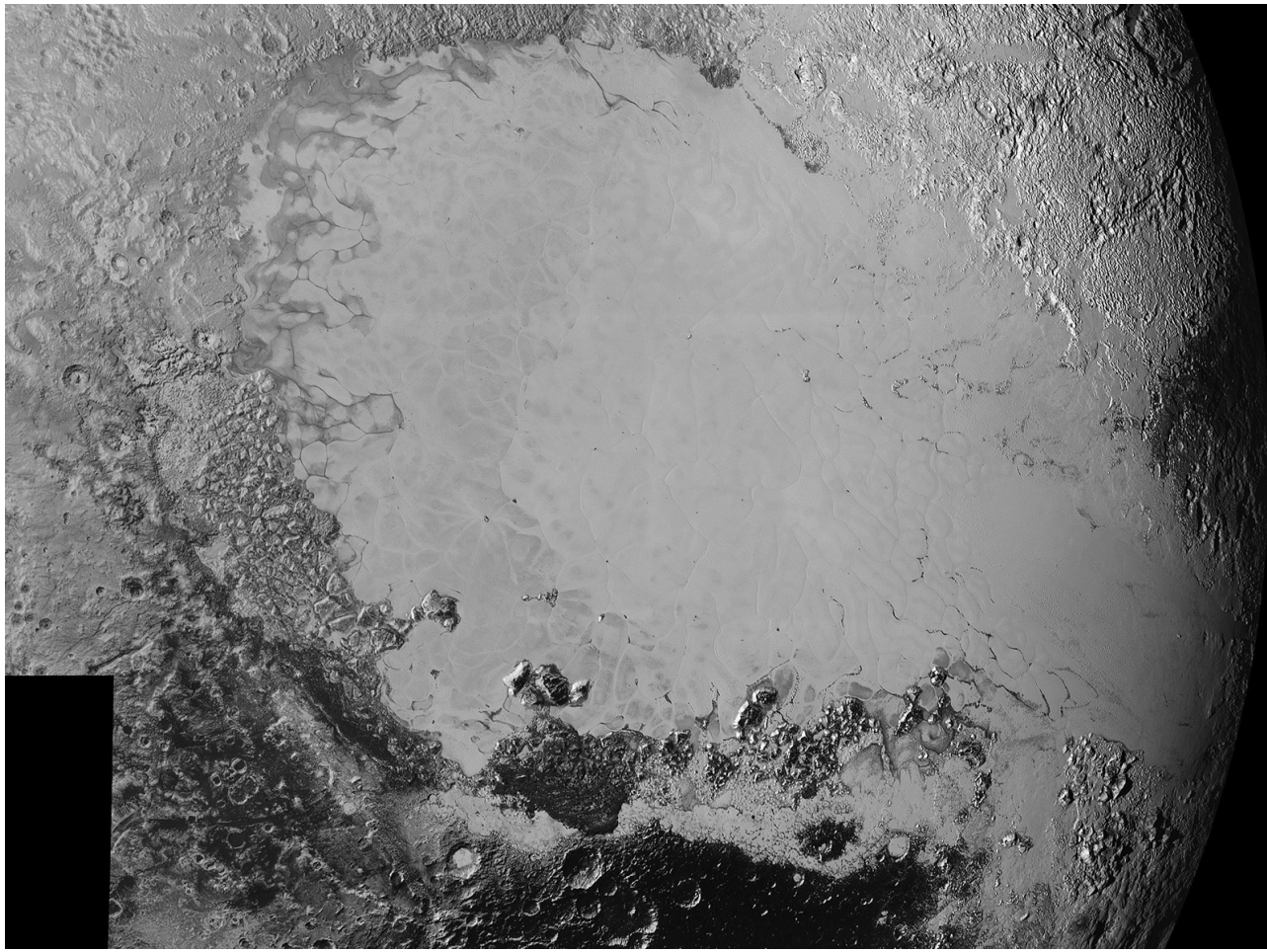
Views of Pluto and Charon based on New Horizons images taken over a 6.4 day period (one rotation) as the spacecraft closed in from 10.2 million kilometres on 7 July 2015 to ~748,000 km on 13 July 2015.

The encounter hemisphere of Pluto is dominated by the heart-shaped region named *Tombaugh Regio*; the western lobe is called *Sputnik Planitia*.

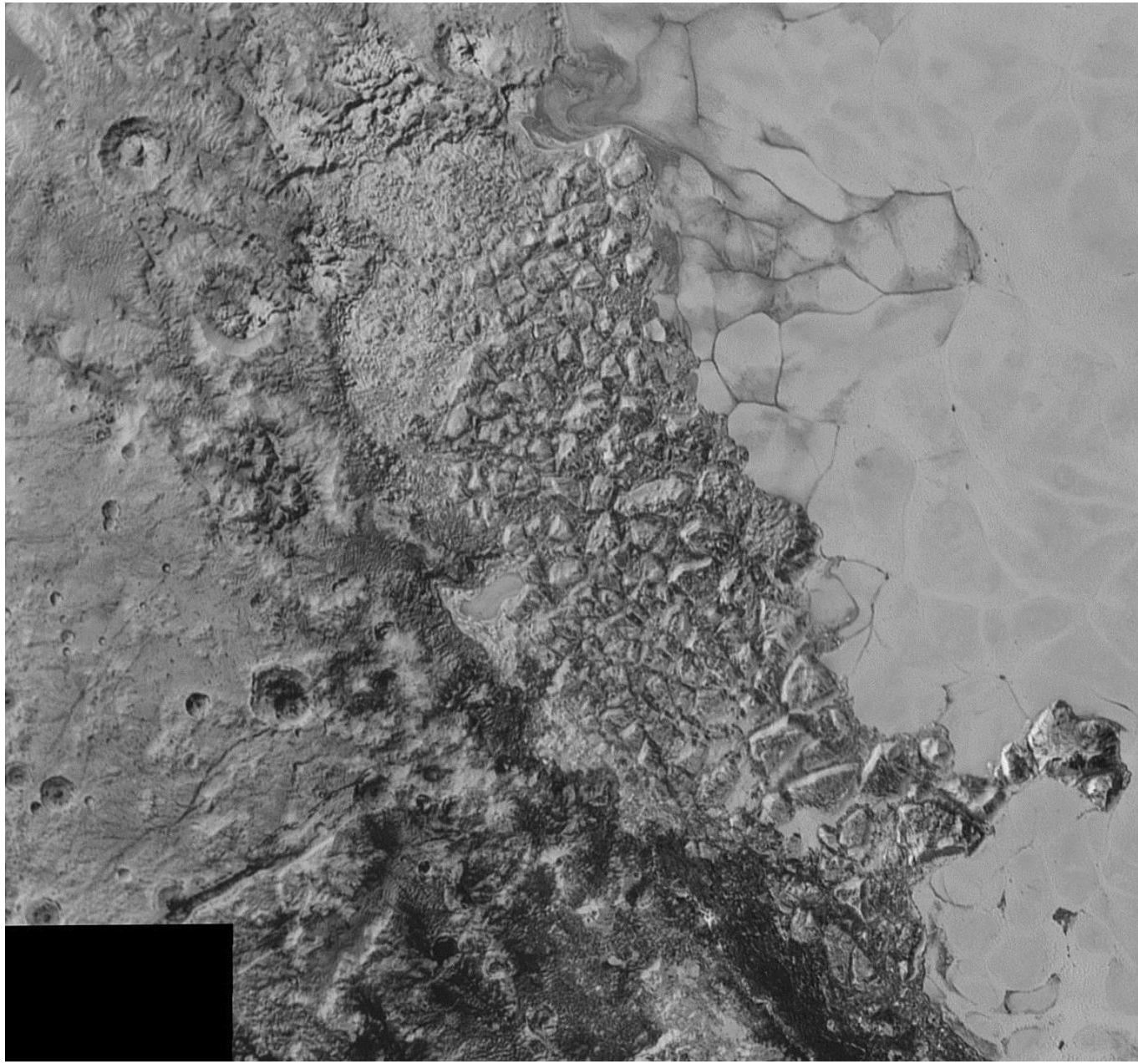
The dark regions contain many craters, as well as several large fractures.


Voyager
Terra
Hayabusa Terra
Djanggawul
Fossae
Al-Idrisi
Montes
Burney
Sputnik
Planitia
Sleipnir
Fossae
Tartarus
Dorsa
Elliot
Hillary
Montes
Virgil Fossae
Adlivun
Cavus
Tenzing
Montes
Tombaugh
Regio

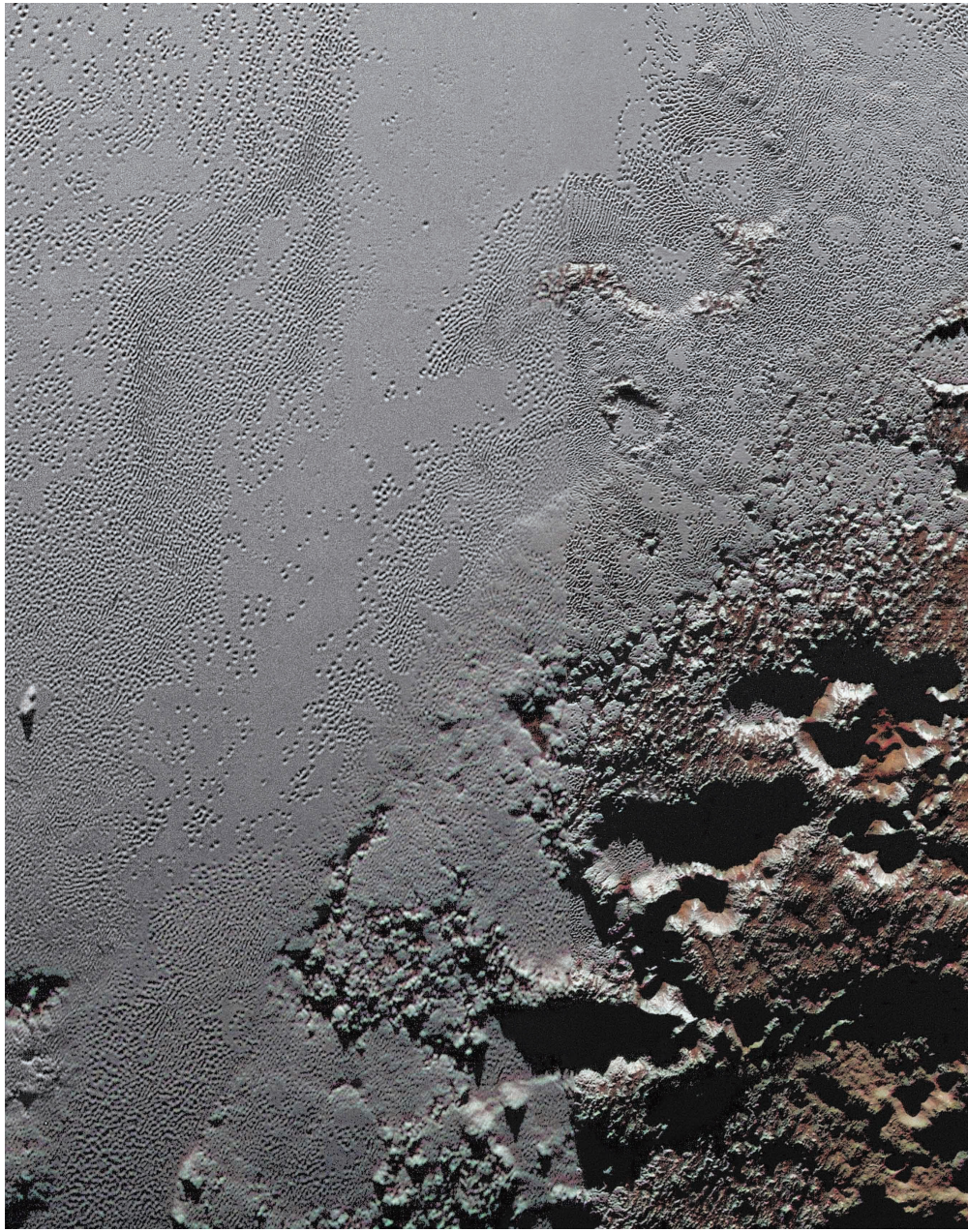
Sputnik Planitia is a deep (3–4 km) depression, about 750 x 1400 km across, filled with bright nitrogen, methane and carbon monoxide ice. There are no visible craters on the ice, so it must be extremely young.



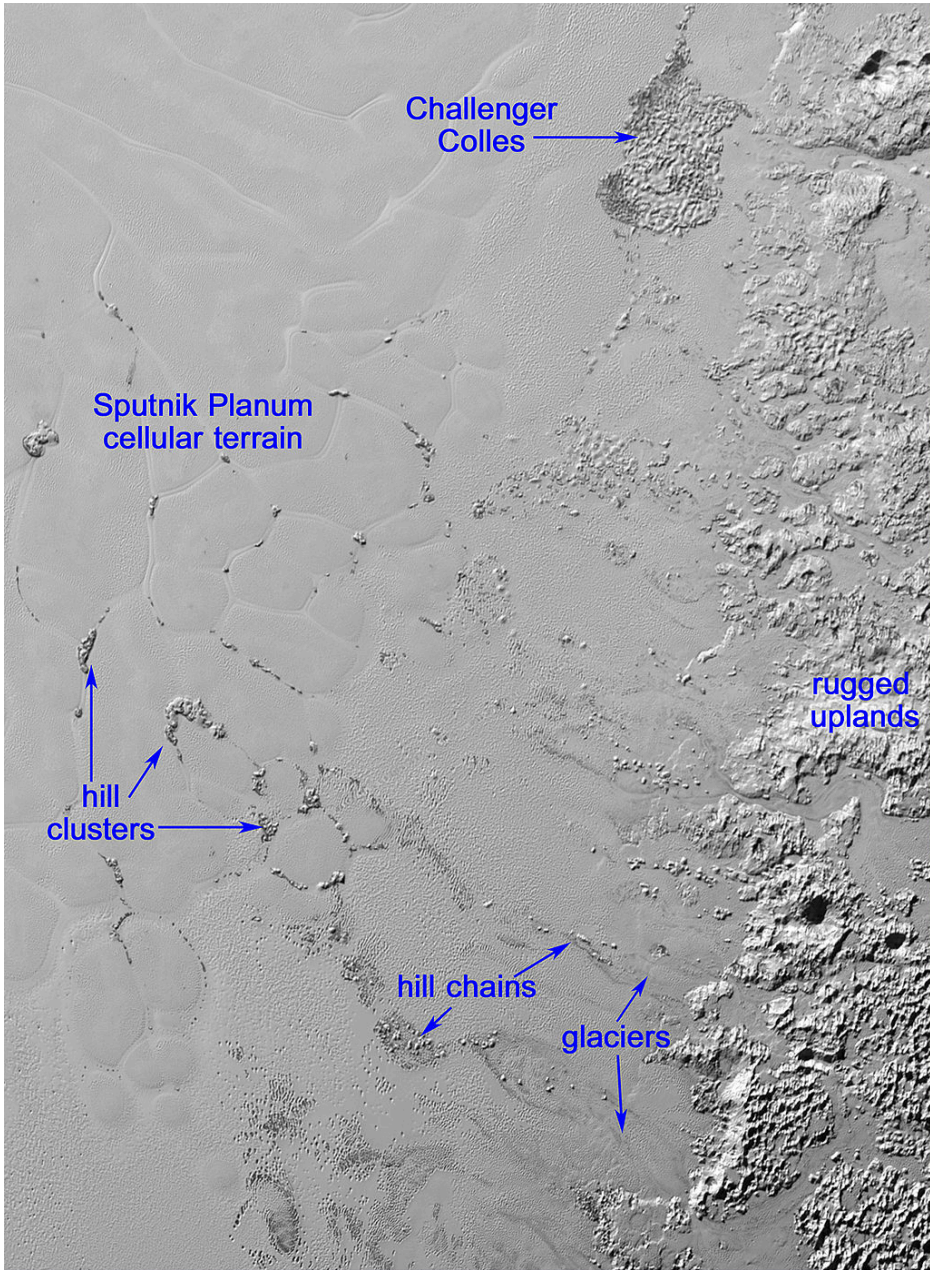
The ice shows polygonal structures which are signs of convection of the nitrogen/carbon monoxide ice. Heat from the interior wells up in the centre of cells (which are about 100 m higher than the edges) and sinks at the margins.



The ice is covered with mysterious pits, which are probably formed by sublimation or evaporation of the ices.

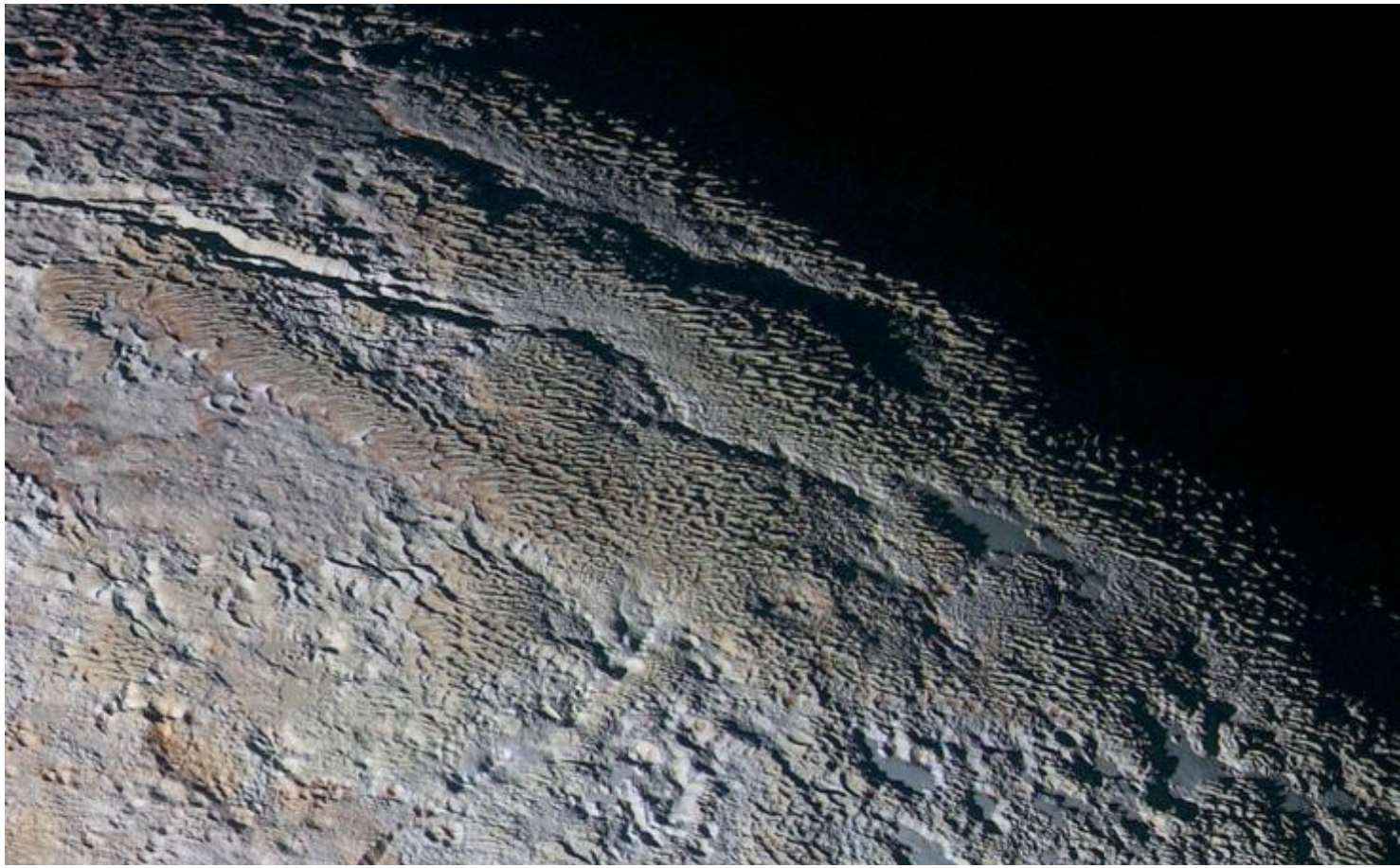


On the eastern edge of Sputnik Planitia is evidence of nitrogen glaciers. Buried in these are numerous, isolated hills that may be fragments of water ice from Pluto's surrounding uplands, floating in a sea of frozen nitrogen and moving over time like icebergs.

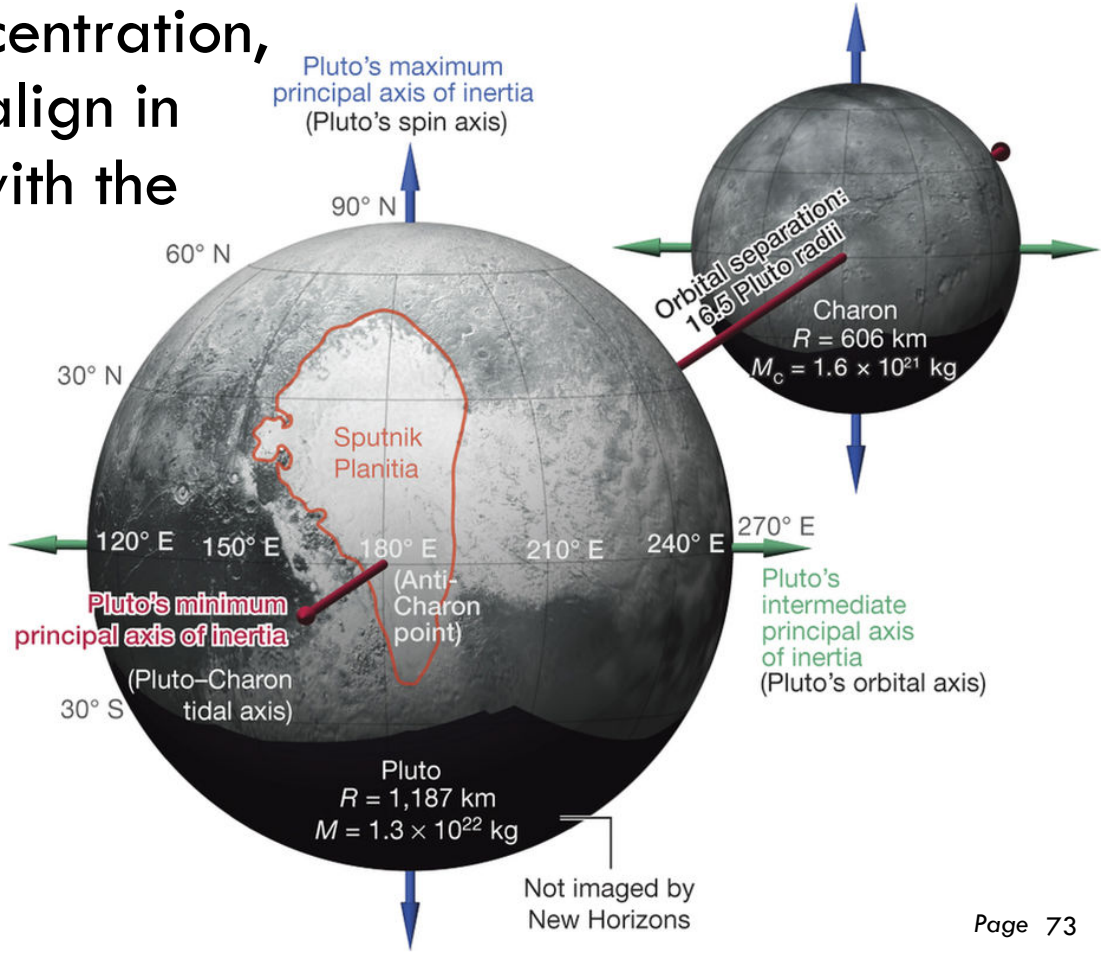


The "shoreline" of Sputnik Planitia

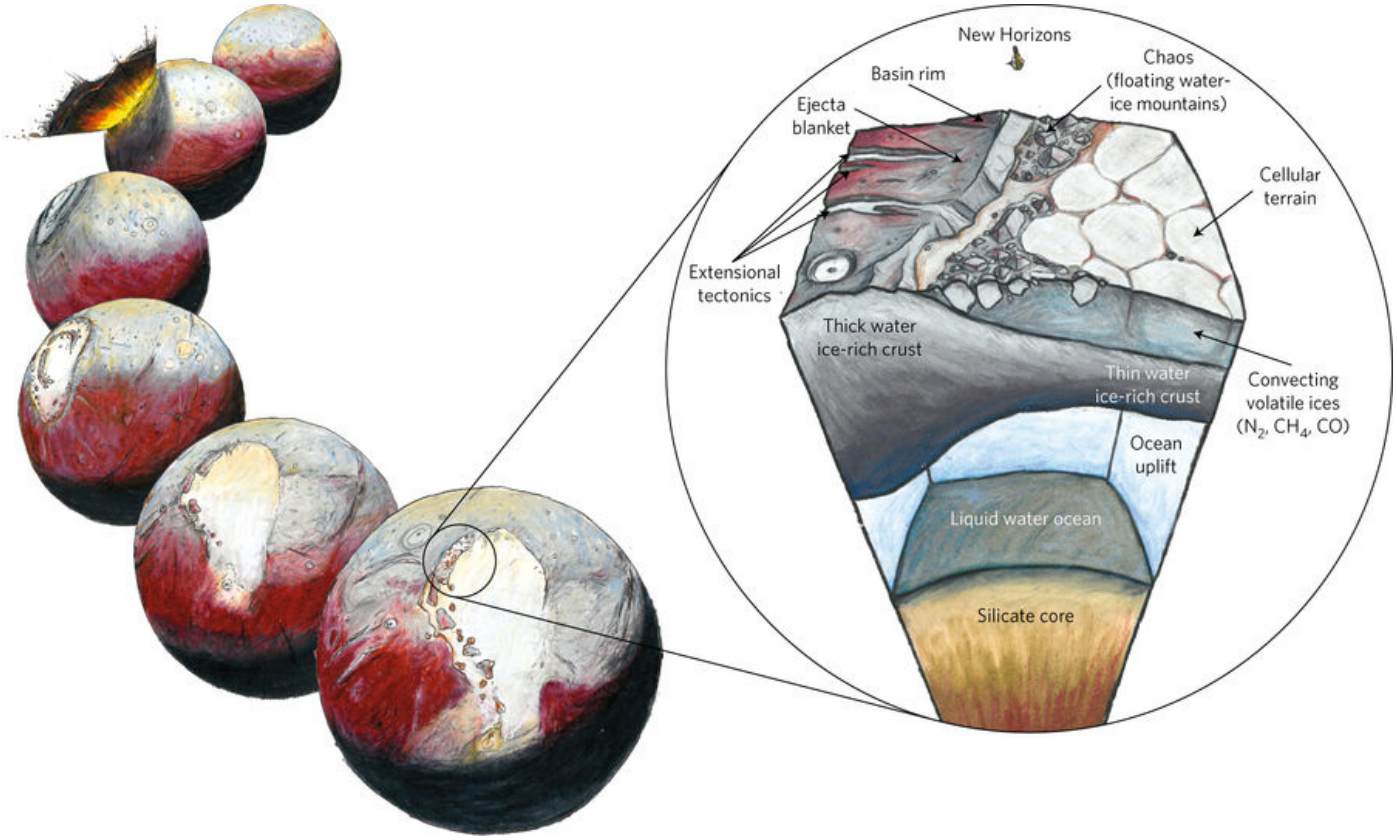
To the east of Tombaugh Regio is a peculiar region which has been called “bladed terrain” or “snakeskin”. This is a series of ice ridges, up to 500 m tall and 3–5 km apart. They appear to be formed from eroding methane ice.

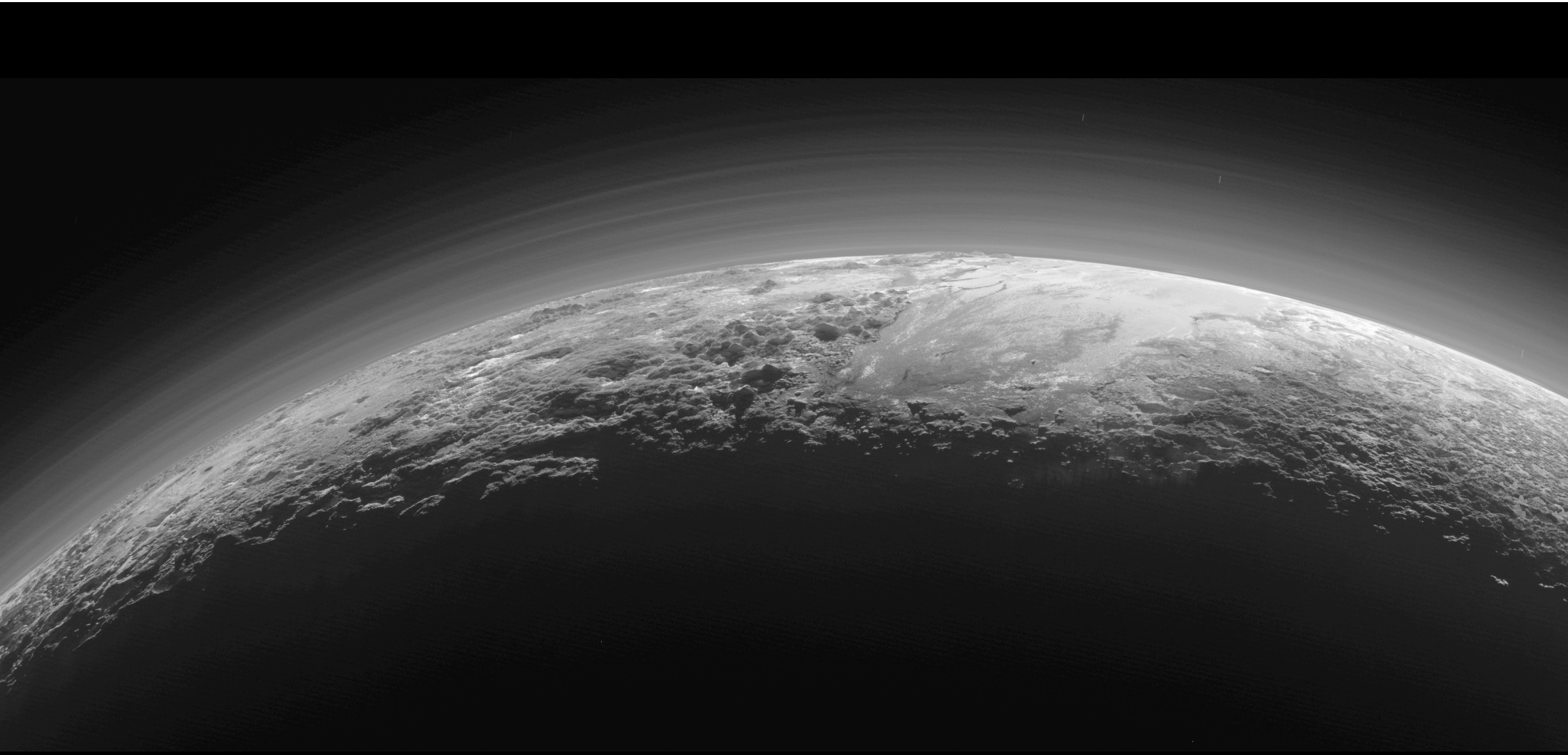


Sputnik Planitia probably fills an old impact basin. The basin is suspiciously close to the tidal axis of Pluto. Recent research suggests that Sputnik Planitia is a mass concentration, and Pluto has reoriented itself to align in a gravitationally favorable way with the Pluto-Charon axis.



This mass concentration might be explained if the crust was thinner under the impact basin, so that a denser liquid-water ocean is closer to the surface at this location. So Pluto might also have a salty ocean underneath its icy crust.

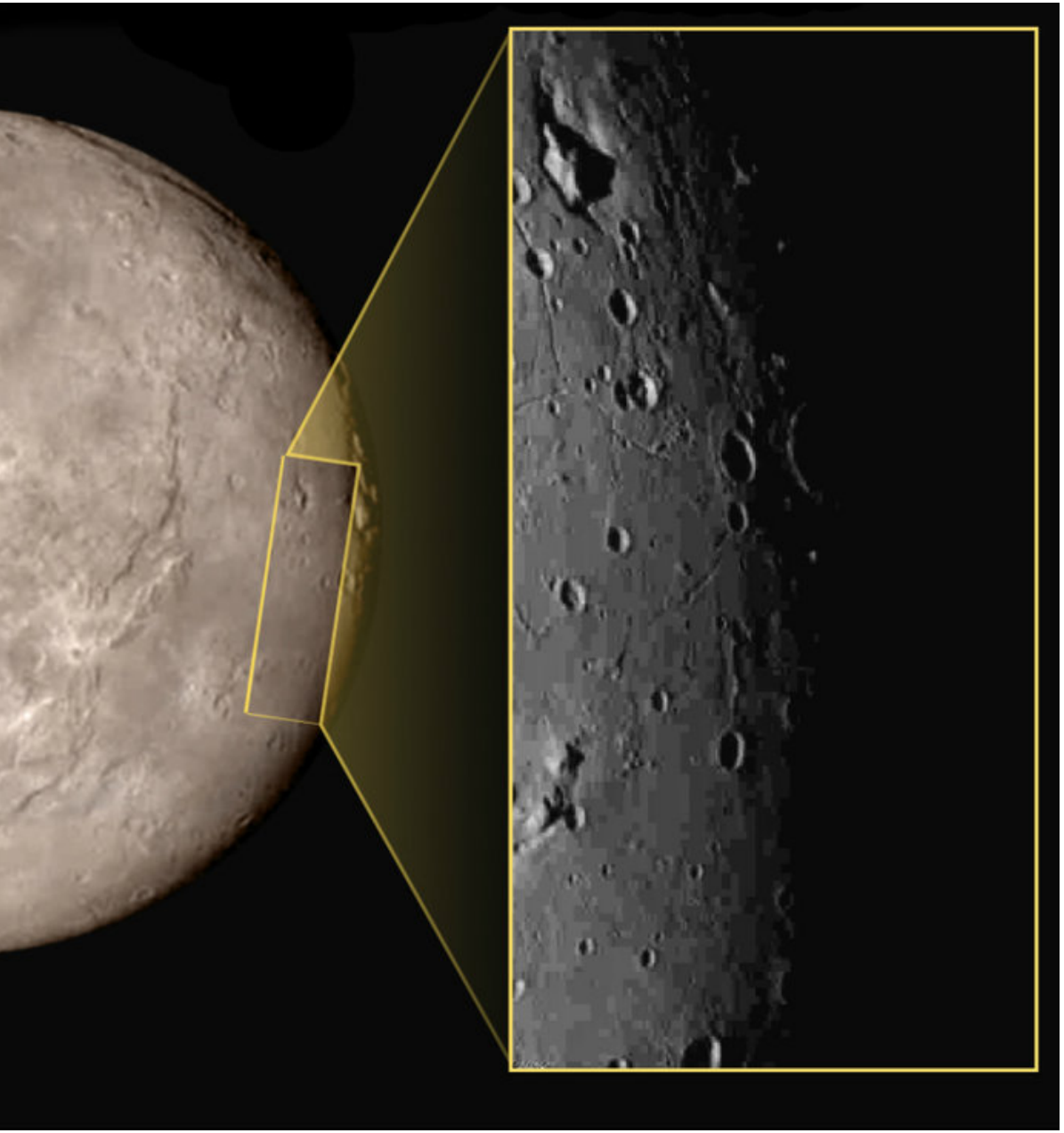




Looking back over Pluto after closest approach, showing mountains, plains, and Pluto's tenuous atmosphere.

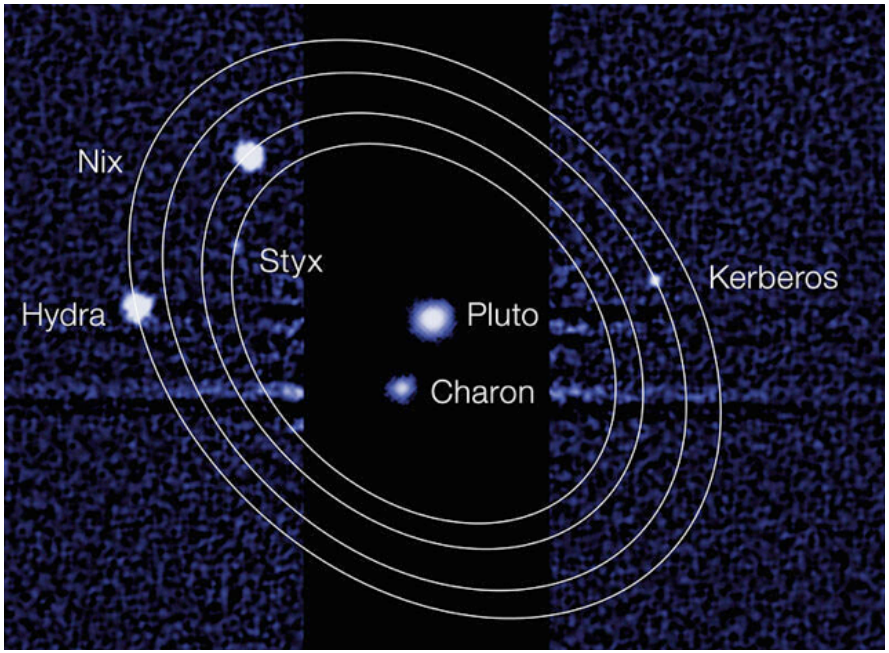
Charon has a peculiar red polar region, and tectonic fractures around its equator which separate the rugged and cratered northern hemisphere from the smoother southern plains.

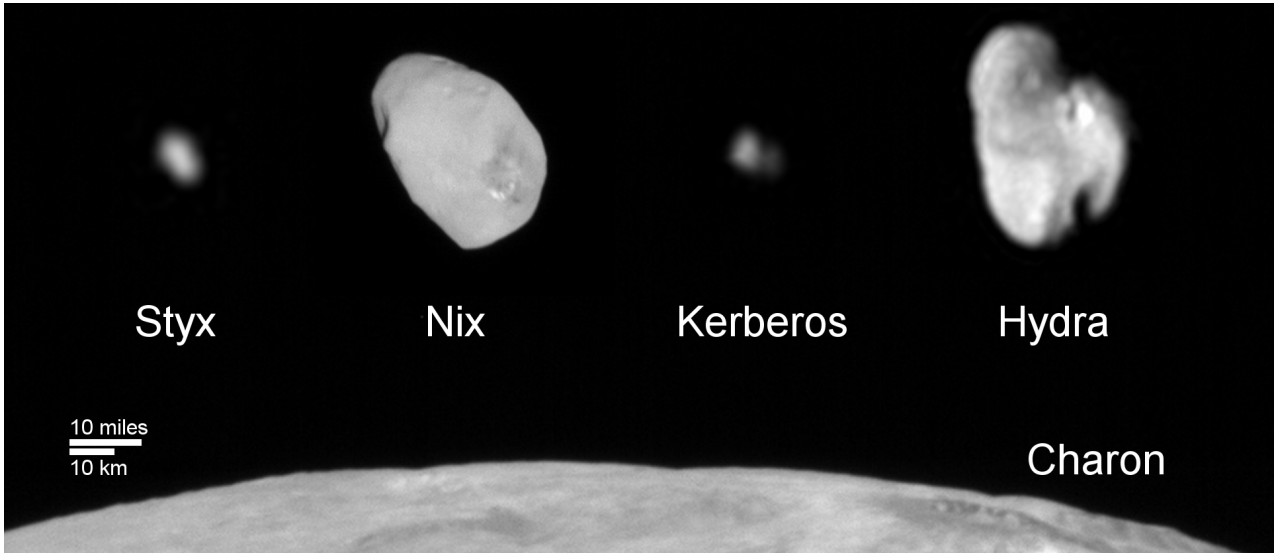
The red region at Charon's pole appears to be due to the condensation of gases that escaped from Pluto's atmosphere. Exposure to sunlight converts these substances to *tholins* – the same organic compounds that give Titan its orange atmosphere.



Charon's surface is dominated by water ice, unlike Pluto, which has mostly methane and nitrogen ice. Its surface also has features not seen on Pluto, like landslides, and a peculiar "mountain in a moat".

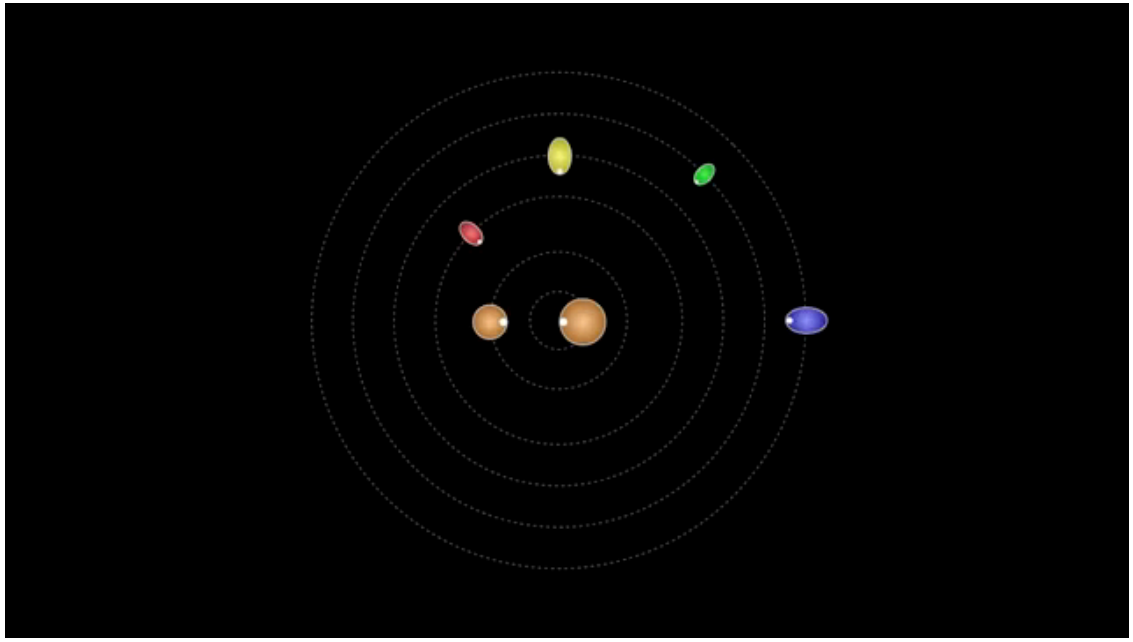
The *Hubble Space Telescope* discovered that Pluto has four more tiny moons: *Nix*, *Hydra*, *Kerberos* and *Styx*. They are between 10 and 50 km across, compared to Charon's 1212 km diameter.





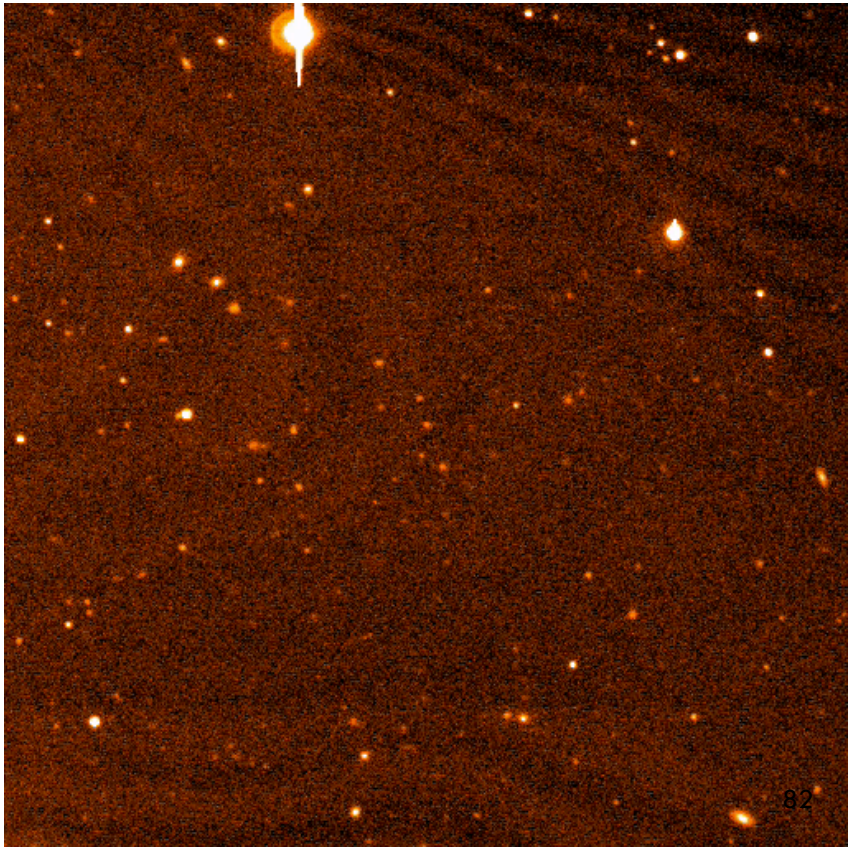
Oddly, *none* of these tiny moons is tidally locked to Pluto: all four of them have peculiar rotation states, with axes pointed every which way, and non-synchronous rotation. Hydra, in particular, rotates once in 10 hours!

The moons appear not to be captured asteroids, but were formed in the Pluto system. They might be collisional fragments from the collision that is presumed to have created Pluto-Charon.

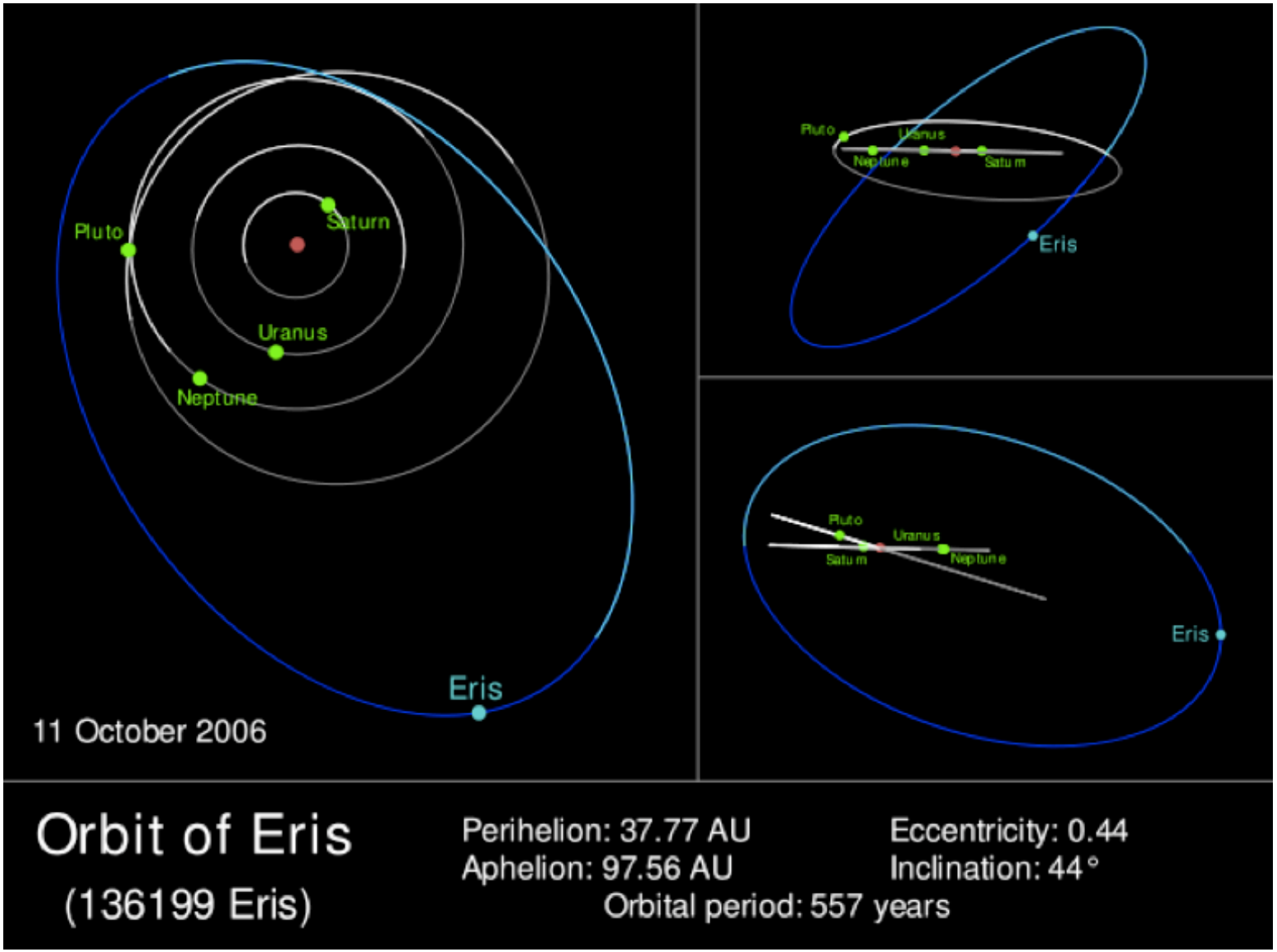



Eris

In 2005, three astronomers searching for Kuiper belt objects found a new object, even larger than Pluto. It was given the temporary designation 2003 UB313, and later called *Eris*. Its orbit is even more eccentric than that of Pluto. Pluto's distance from the Sun varies between 30 and 50 AU over its 250 year orbit, while Eris moves from 38 to 97 AU over its 560 year orbit.



The three discovery images, taken 1.5 hours apart, showing the new object moving very slowly compared to the background stars.

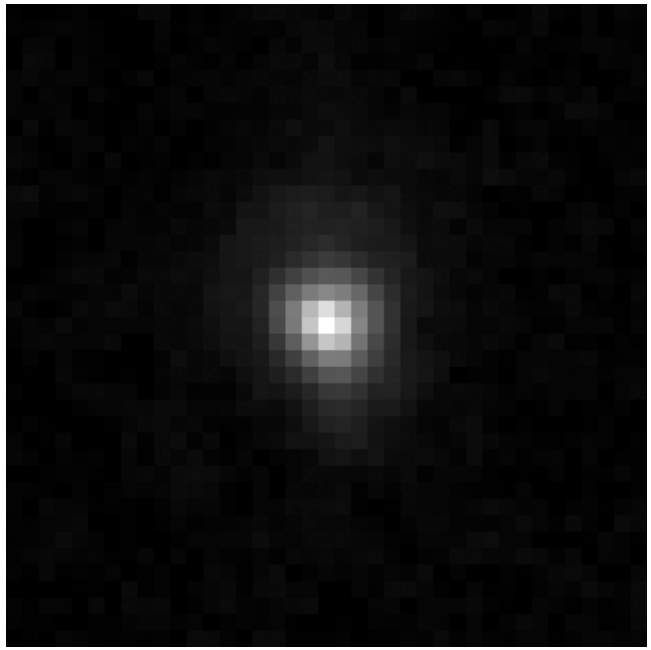


Orbit of Eris

(136199 Eris)

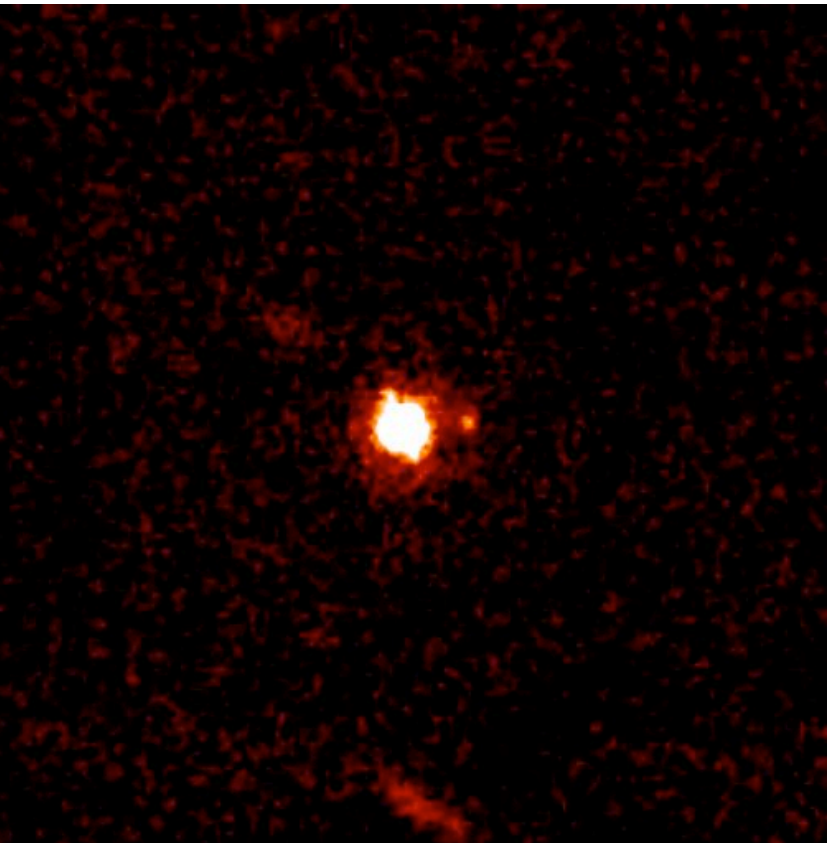
Perihelion: 37.77 AU
Aphelion: 97.56 AU
Eccentricity: 0.44
Inclination: 44°
Orbital period: 557 years

Eris is almost exactly the same size as Pluto: its diameter was measured using the stellar occultation to be 2326 ± 12 km, making it slightly smaller than Pluto's 2372 ± 4 km. The surface is considerably brighter than Pluto's, with an albedo of 0.86 instead of 0.6. This is brighter than any other Solar System object except Enceladus. Eris' mass is actually larger than Pluto's, meaning it is significantly denser.



The best image of Eris, taken by Hubble.

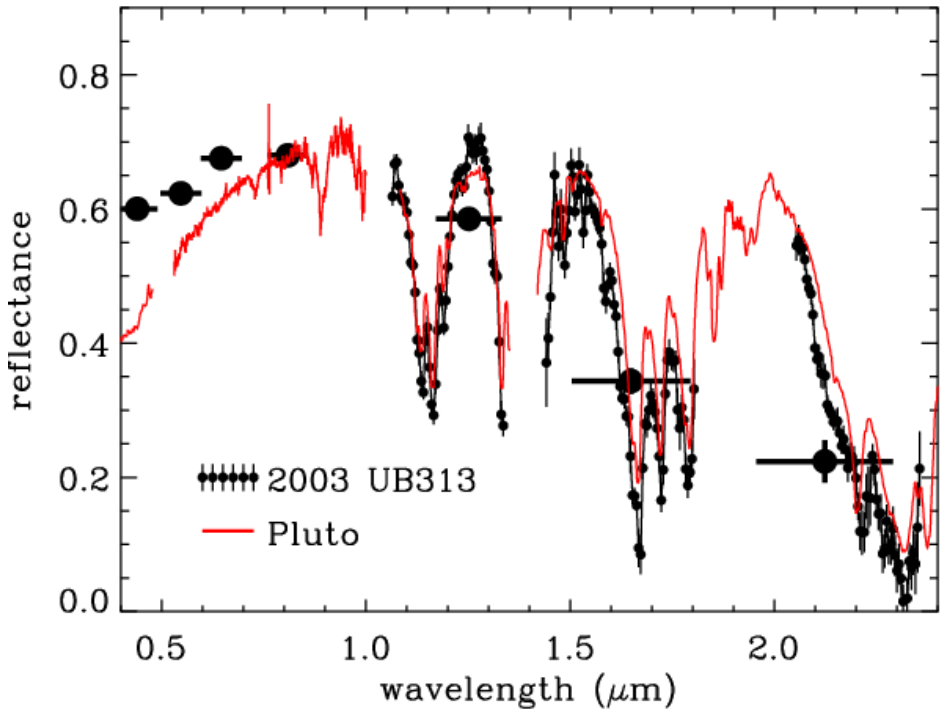
In 2006, after the decision regarding the definition of a planet, the new body was given the name *Eris*, the Greek goddess of warfare and strife. Eris' satellite is called *Dysnomia*, Eris' daughter and the demon spirit of lawlessness.



Eris is the most distant object ever seen in orbit around the sun, more than 3 times more distant than the next closest planet, Pluto.

Keck adaptive optics image of Eris, showing its moon Dysnomia (to the right of centre)

The best suggestion for Eris' brightness is that, since the planet is now at aphelion and as far away from the Sun as it gets, its atmosphere has frozen completely, leaving the planet with a bright covering of several inches of frozen methane and nitrogen. Over the next 280 years, the surface will warm from −243°C to −217°C, allowing the nitrogen and methane to evaporate, possibly revealing a surface more like Pluto's.



Infrared reflectance of Eris and Pluto. The dips are all due to solid frozen methane.

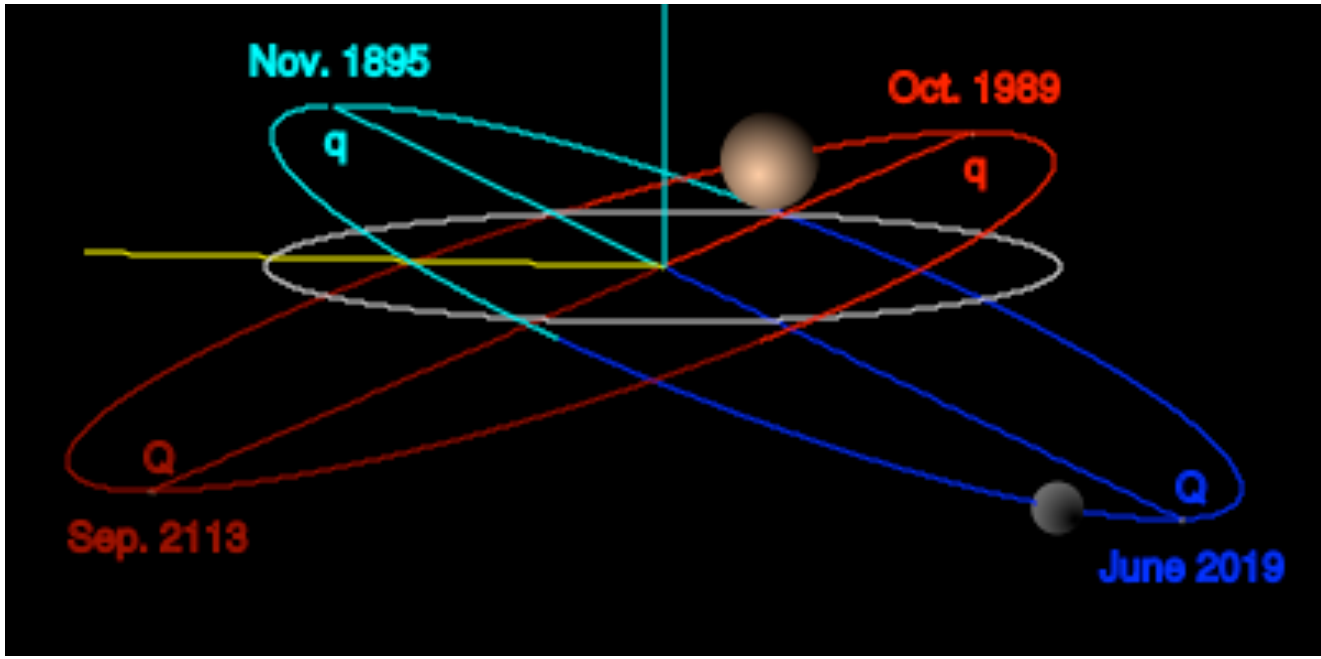
Eri and Pluto are the largest of the *trans-Neptunian objects* (TNOs). As of 2011, there were more than 2000 objects known beyond the orbit of Neptune. At least eight TNOs (plus Charon) have diameters of more than 900 km. The total mass of the Kuiper Belt is only a few times the mass of our Moon.

Name	Diameter	Class	Discovery
Eris	2326	SDO	2005
Pluto	2372	KBO	1930
(Charon)	*1205*	*KBO moon*	*1978*
Makemake	1430	KBO	2005
Haumea	1379	KBO	2005
Sedna	995	SDO?	2003
Orcus	917	KBO	2004
Quaoar	1070	KBO	2002
Varuna	936	KBO	2000
Ixion	800	KBO	2001
Salacia	854	KBO	2004
2002 MS_4	934	KBO	2002
2007 OR_{10}	1280	SDO	2007

There are several sub-groups of TNOs:

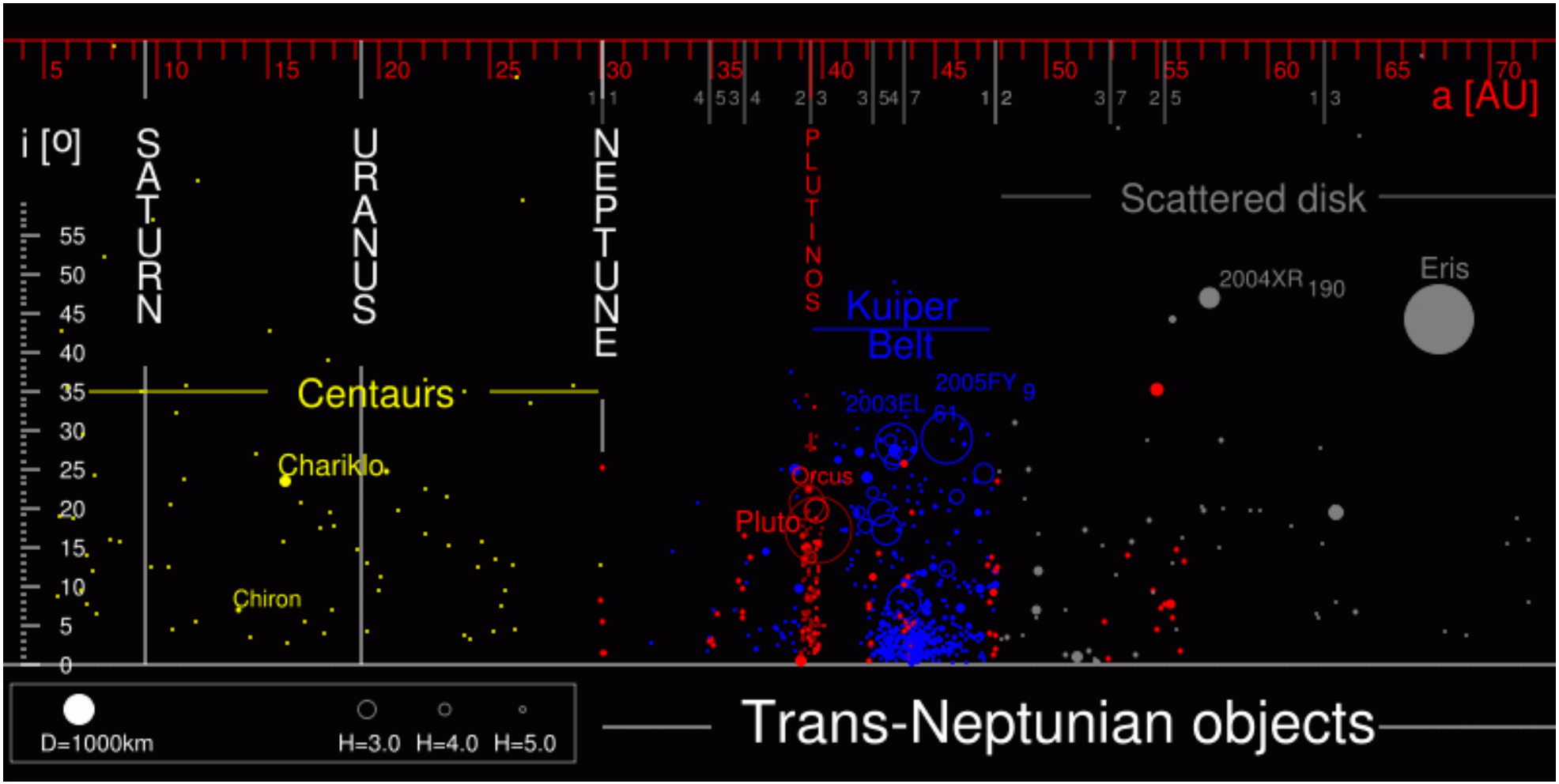
- *Plutinos*, which are in 3:2 resonance with Neptune: these form the inner part of the Kuiper belt; e.g. Pluto
- *Classical Kuiper belt objects* (also called cubewanos), which are beyond Neptune but not in a resonance; e.g. 1992 QB1, Quaoar, Varuna
- *Scattered disc objects*, which are in larger and much more eccentric orbits; e.g. Eris, Sedna
- *Neptune Trojans*, which are in 1:1 resonance with Neptune and lead or trail it, maintaining – on average – approximately equal distance from Neptune and the Sun

Orcus, the 6th-largest dwarf planet, is sometimes called the anti-Pluto. Like Pluto, it is in a highly-inclined orbit in a 2:3 resonance with Neptune (making it a *plutino*), but is always on the opposite side of the Sun from Pluto.

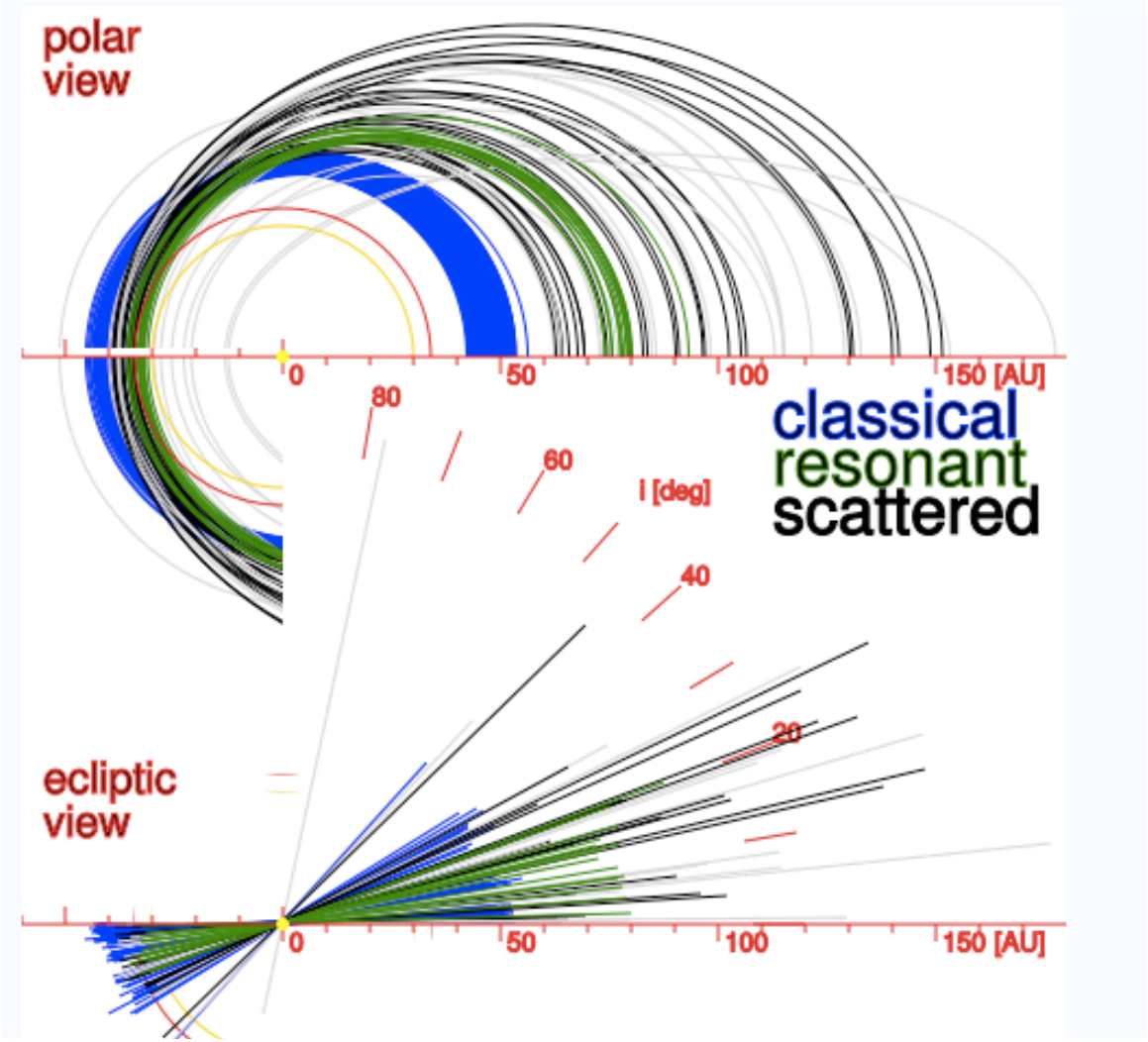


The orbits of Orcus (blue), Pluto (red) and Neptune (grey). Orcus and Pluto are shown in the April 2006 positions. The dates of their perihelia (q) and aphelia (Q) are also marked.

The University of Sydney



Small solar-system bodies. Resonance objects are shown in red, Kuiper Belt objects in blue, and scattered disk objects in grey.

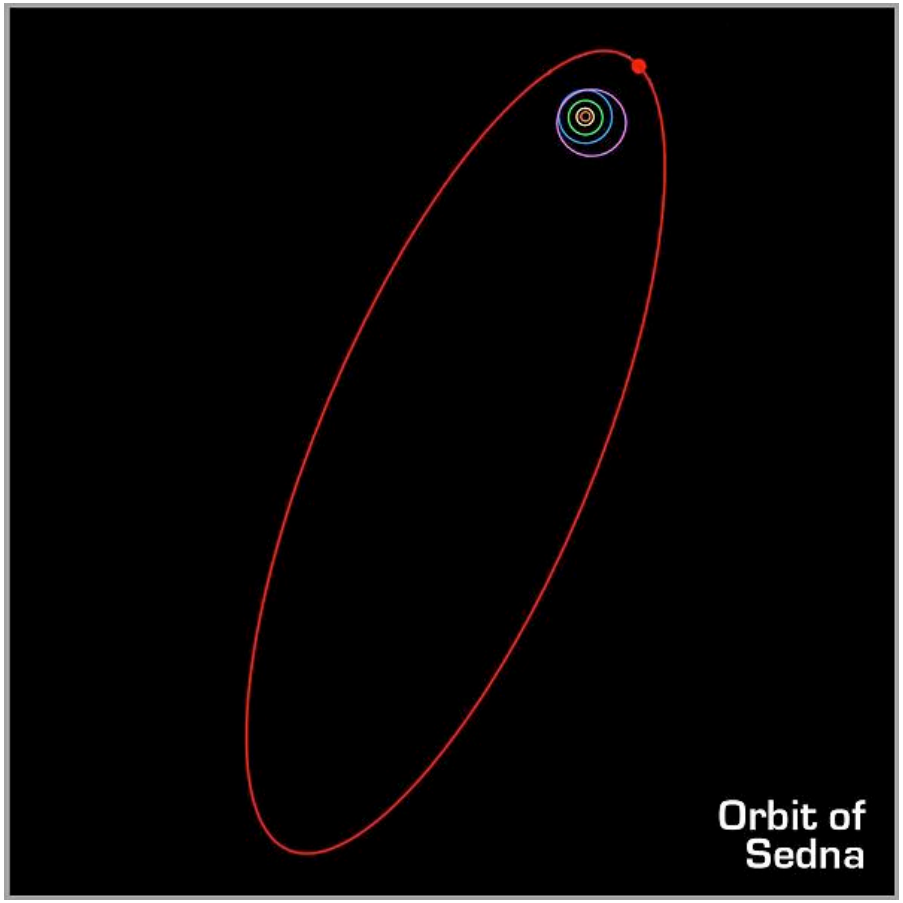


Orbits of the cubewanos (blue), resonant (green) and scattered disk objects, from above and side-on. Yellow represents Neptune's orbit.

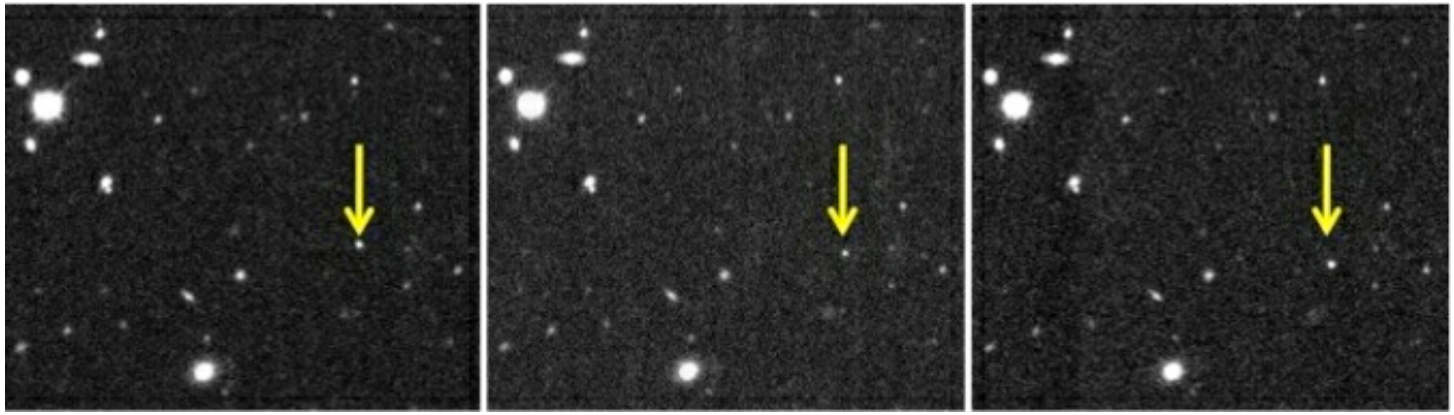
Objects in the inner part of the Kuiper Belt have moderately eccentric orbits, whereas objects further out (beyond about 50 AU) have orbits that are much more eccentric and much more tilted to the ecliptic.

Sedna is one of the most distant objects in the Solar System. It is currently three times as far from the Sun as Neptune, and has a highly elliptical orbit which takes 11,400 years to go round the Sun.

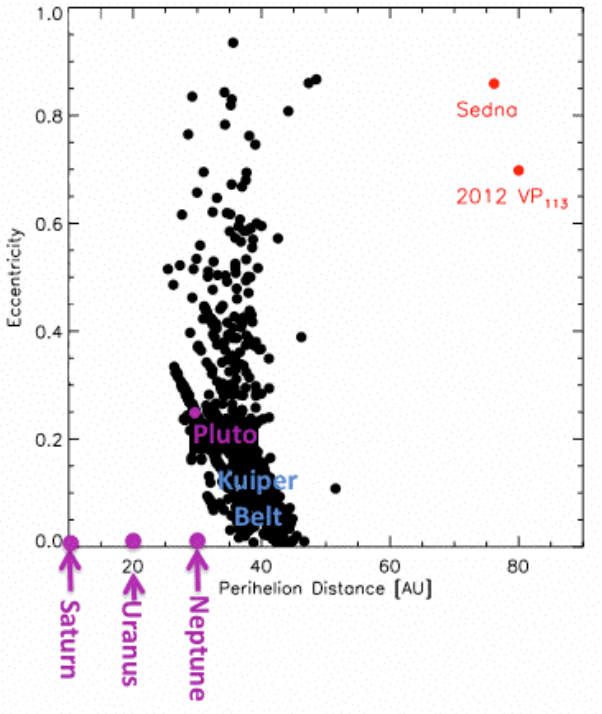
Sedna's orbit is very hard to explain. It must have been pulled into its current orbit by gravitational interaction with another body: another star, or possibly a Neptune-mass planet in the Oort cloud.



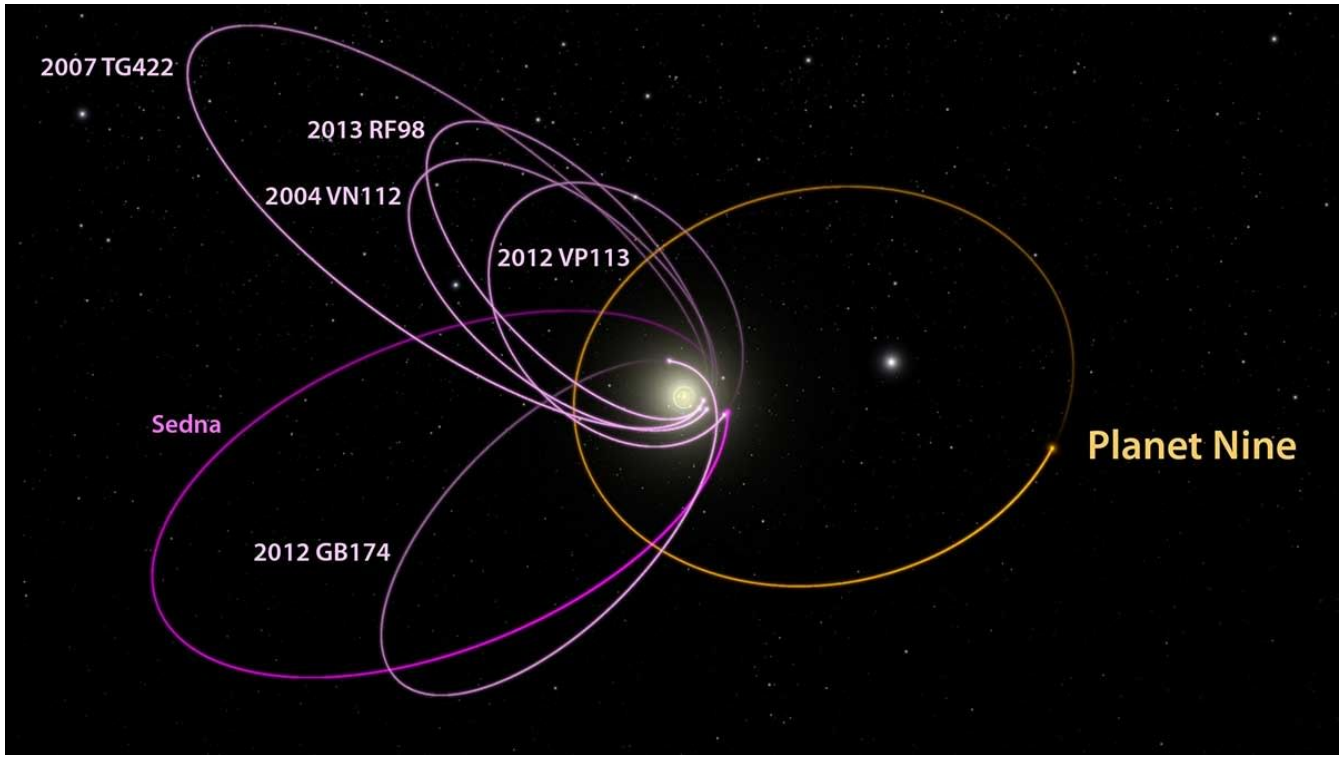
A second Sedna-like object was found in 2012. This new object, 2012 VP113, has a perihelion distance of 80 AU, compared to Sedna's 76 AU. At its furthest, it is about 450 AU from the Sun.



Discovery images of 2012 VP113 taken about 2 hours apart on Nov. 5, 2012. The motion of 2012 VP113 stands out compared to the steady state background of stars and galaxies.

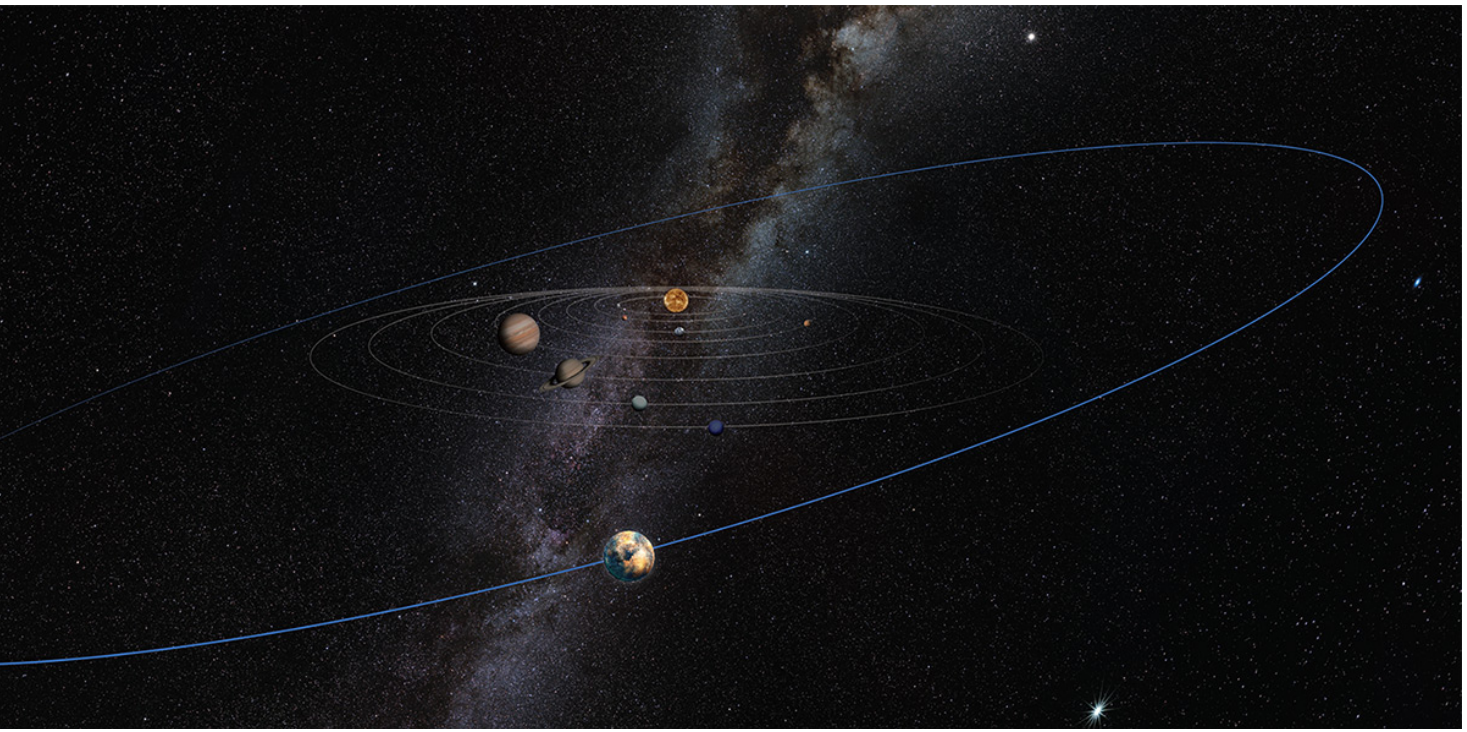


These two objects have orbits sufficiently different from the other objects in the Solar System that they may represent part of the inner Oort cloud. In fact, the similarity in the orbits may suggest there is an unknown body (a super-Earth?) at hundreds of AU, shepherding these objects into similar orbital configurations.



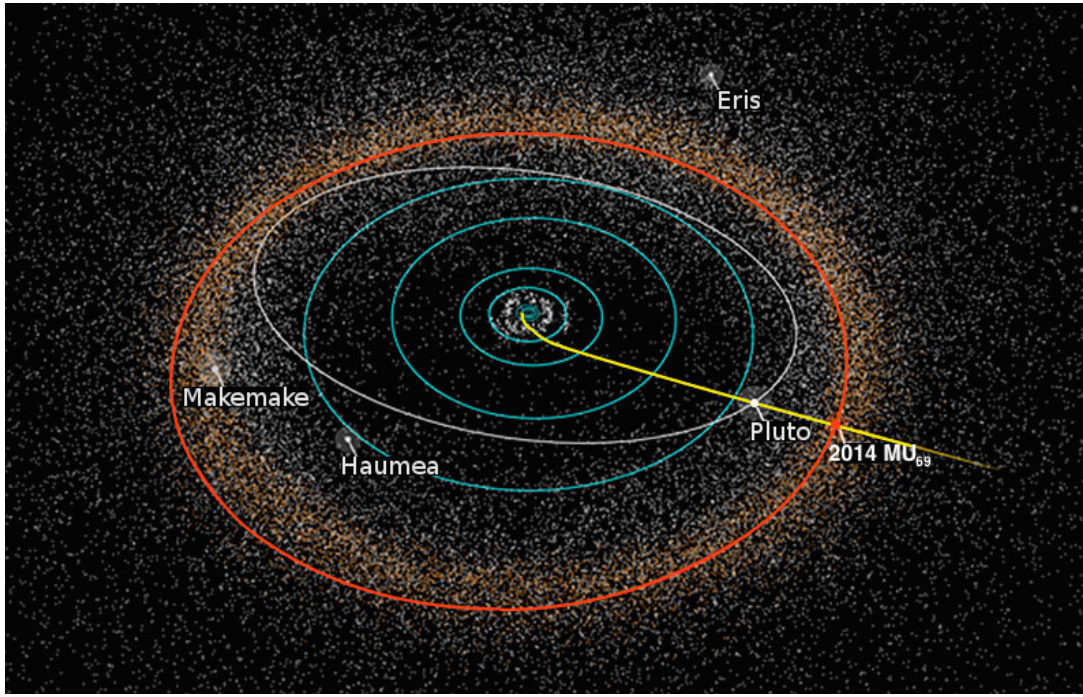
Six TNOs follow elliptical orbits that point in the same direction and are similarly tilted away from the plane of the solar system

Other scientists think there might be other large objects still to be found closer to home. Based on peculiar warps in the orbits of Kuiper Belt objects, they suggest there might be a Mars-sized planet somewhere around 50–80 AU from the Sun in a tilted orbit which is disturbing these objects.



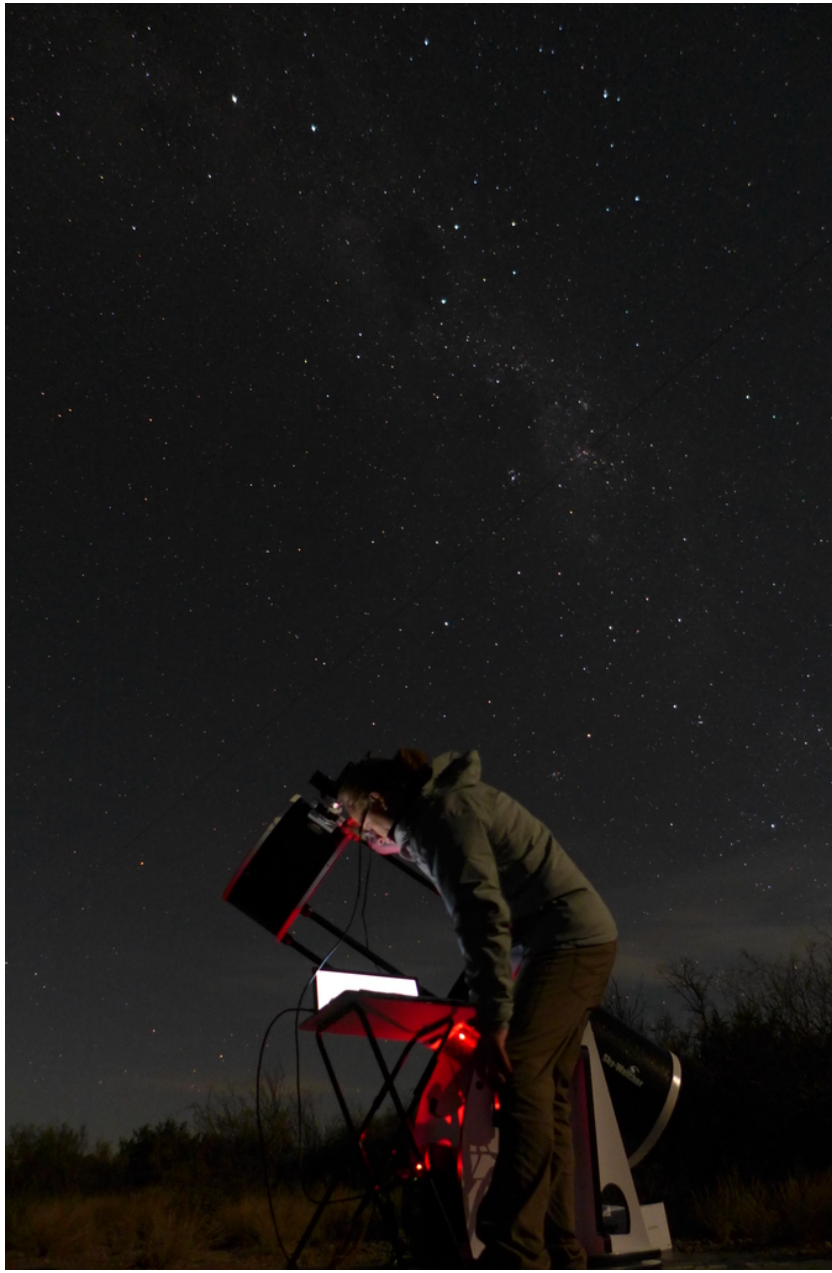
When *New Horizons* launched in 2006, it was proposed that after the Pluto encounter, it could be sent to do a flyby of another Kuiper Belt object. Unfortunately, after passing Pluto, a suitable target had not yet been identified, despite ten years of searching.

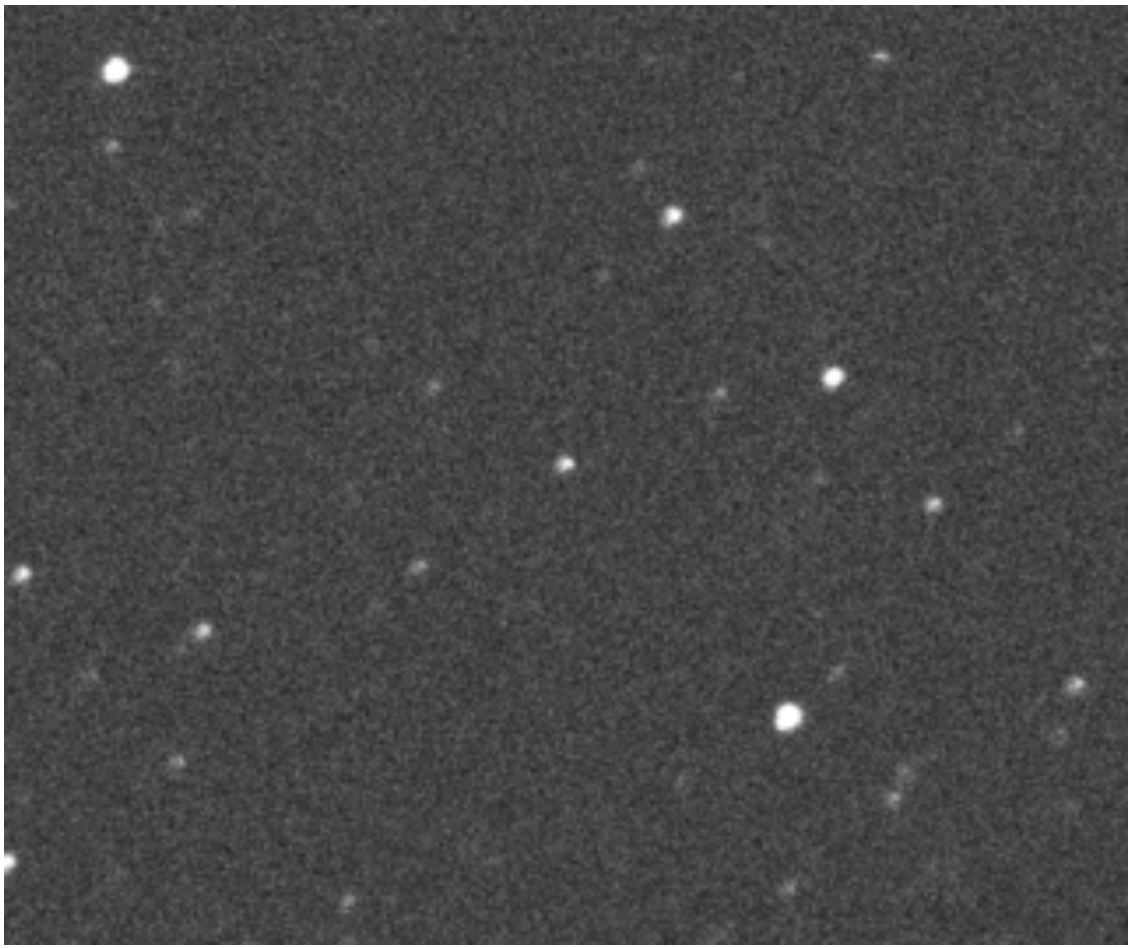
Finally, in 2014 a handful of reachable objects were identified by the *Hubble Space Telescope*, and in 2015, it was announced that *New Horizons* will fly past an object called *2014 MU_{69}* on 1 January 2019.

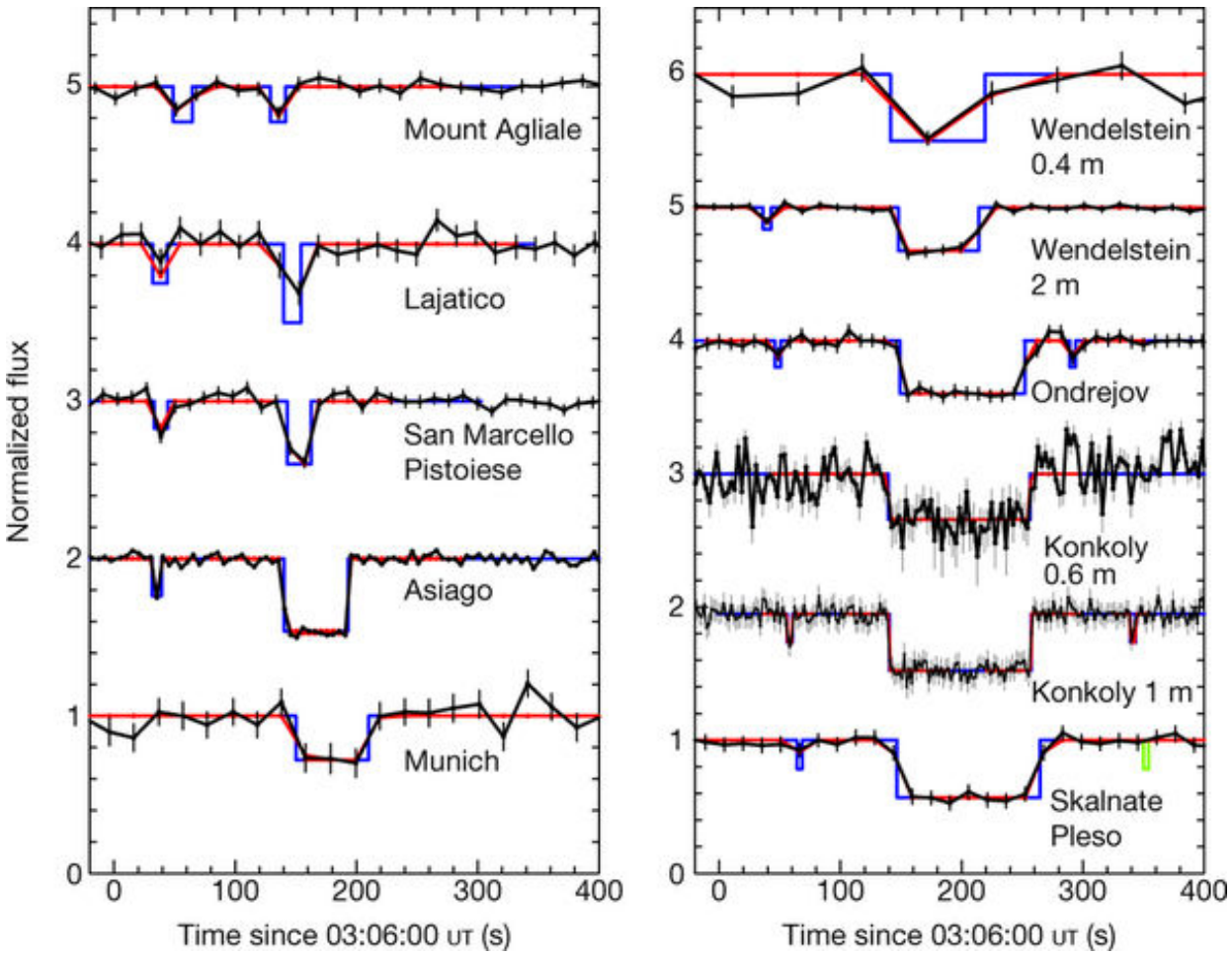


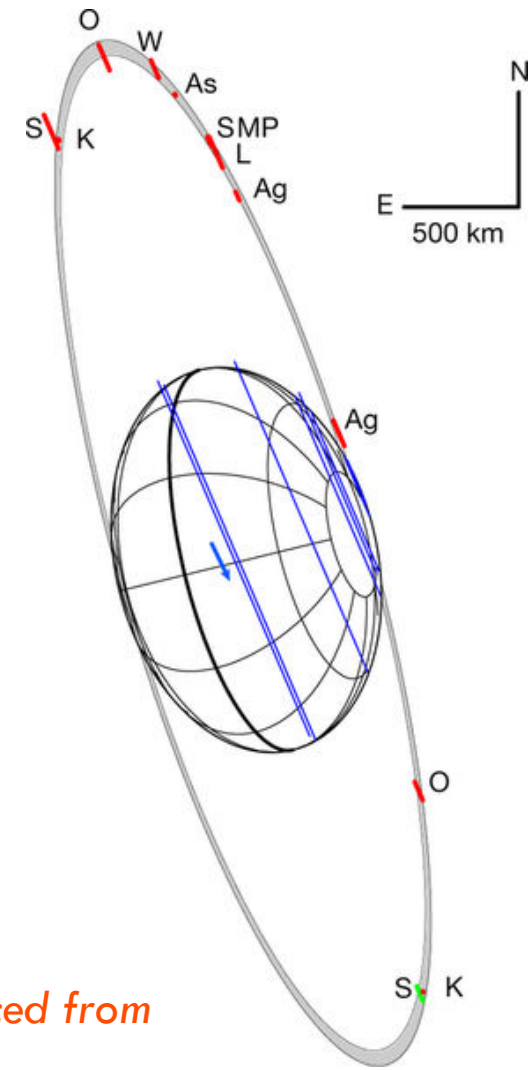
MU_{69} is much smaller than Pluto, only about 30 km across.

Earlier this year, a team of mobile telescopes was sent to Argentina to observe MU_{69} crossing in front of a star – a *stellar occultation*. By observing the shadow of MU_{69} from five different places, astronomers were able to get information about MU_{69}'s shape.









Stellar occultation of Haumea from different observatories, and the model deduced from the observations, including a ring.

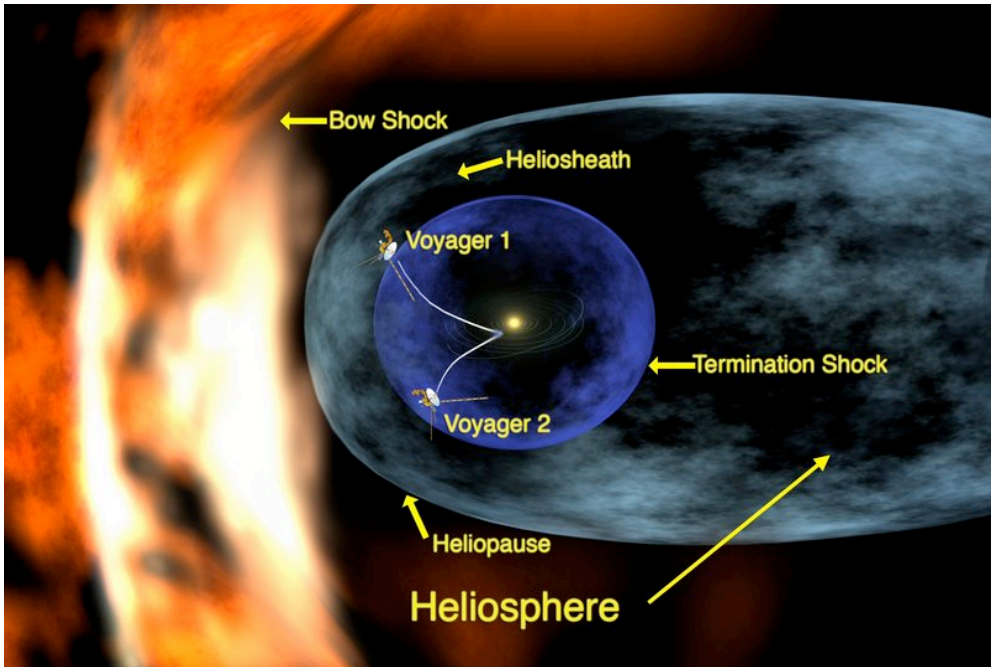
Much to everyone's surprise, the observations suggest that MU_{69} is either very elongated, or possibly double. MU_{69} is a classical Kuiper belt object, a frozen remnant from the Solar System's deep past. The plan is for *New Horizons* to approach much closer to it than it did to Pluto, coming within just 3500 km at closest approach.

NASA has just announced a competition to choose a nickname for MU_{69}.

MU_{69} could be a single body with a large chunk taken out of it, or two bodies that are close together or even touching.

And beyond…

The *Voyager* missions are currently leaving the Solar System. *Voyager 1* is escaping at about 3.6 AU per year, 35° degrees north out of the ecliptic plane. *Voyager 2* is escaping at about 3.3 AU per year, 48° south out of the ecliptic plane. In December 2004, *Voyager 1* crossed the termination shock, where the solar wind slows. In 2012 there were signs it was crossing the heliopause and entering interstellar space.



NUMBER OF TIMES *VOYAGER 1* HAS LEFT THE SOLAR SYSTEM

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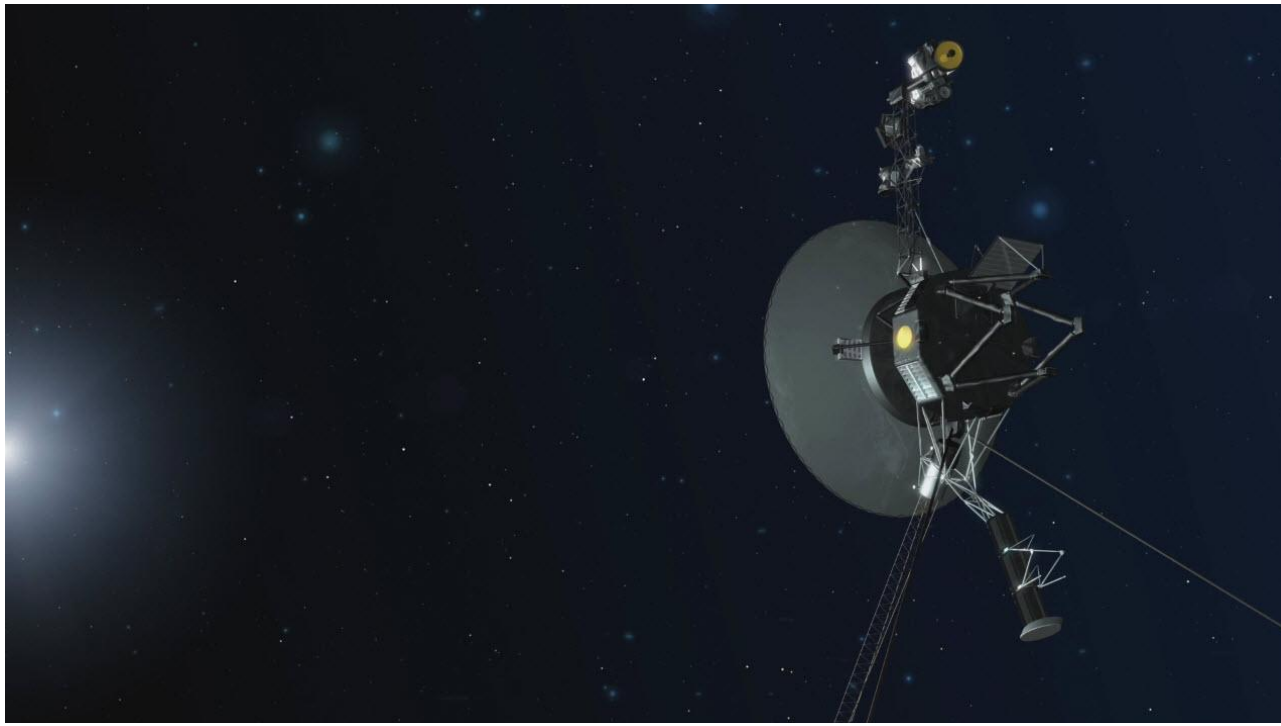
Voyager 1 is currently nearly 21 billion km from the Sun, at a distance of about 140 AU (more than 3 times the distance of Pluto), and gaining 3.6 AU each year.

Signals are steadily fading. Both spacecraft are powered by about 249 watts from the radioactive decay of on-board plutonium-based generators, but that power drops by about 4 watts every year. The spacecraft will run out of power by about 2025.



Next week

... we're going to tie the whole thing together,
and look at how the planets formed.

Further reading

There aren't very many books particularly about the outer planets. A few interesting ones, in addition to the more general references I've given already:

- "**Atlas of Uranus**" by Garry Hunt and Patrick Moore (Cambridge, 1989) tells the story of Uranus after the Voyager 2 fly-by.
- The story of the discoveries of Uranus and Neptune is told in "**The Neptune File: Planet detectives and the discovery of worlds unseen**" by Tom Standage (Allen Lane, 2000). It's entertaining, though it feels a bit like he's trying to stretch it to book length. The story of the discovery of extra-solar planets has been better told elsewhere, for instance. Still, an enjoyable read.
- "**Beyond Pluto: Exploring the outer limits of the solar system**" by John Davies (Cambridge, 2001) tells the story of the discovery of the Kuiper Belt and trans-Neptunian objects.
- Govert Schilling tells the story of the discovery of the outer solar system, going all the way back to the discovery of Uranus and the asteroids, in "**The Hunt for Planet X: New worlds and the fate of Pluto**" (Springer, 2009) The book was being written during the hoopla about Pluto, and he ties the stories together very nicely. A good read.
- Mike Brown has written a very entertaining book called "**How I Killed Pluto: And why it had it coming**". Which kind of says it all.
- The home page for the "New Horizons" mission, which flew past Pluto and Charon and on to the Kuiper Belt, is at http://pluto.jhuapl.edu/

- There's a terrific page on the discovery of Neptune at http://www-history.mcs.st-andrews.ac.uk/HistTopics/Neptune_and_Pluto.html
- Mike Brown's page about the discovery of Eris and the most recent observations of it is at http://web.gps.caltech.edu/~mbrown/planetlila/
- His page about trying to draw the Solar System to scale is interesting reading: http://www.mikebrownsplanets.com/2009/08/planetary-placemats.html. Hal Levison has another interesting page called "**A Hand-Waving Derivation of Planethood**" at http://www.boulder.swri.edu/~hal/planet/index.html
- Scott Shepherd, one of the discoverers of 2012 VP113, has a very interesting page about the discovery at "**Beyond the Edge of the Solar System: The Inner Oort Cloud Population**" http://home.dtm.ciw.edu/users/sheppard/inner_oort_cloud/
- Emily Lakdawalla has a terrific blog post about the search for possible KBO targets for New Horizons: http://www.planetary.org/blogs/emily-lakdawalla/2014/10151024-finally-new-horizons-has-a-kbo.html
- The competition to name MU_{69} is at http://www.frontierworlds.org/

Sources for images used:

All images with PIA numbers are from the NASA Planetary Photo Journal https://photojournal.jpl.nasa.gov/

- Voyager: from NSSDC Voyager Project Information http://nssdc.gsfc.nasa.gov/planetary/voyager.html
- Voyager trajectories: from UCR Space Physics http://spacephysics.ucr.edu/index.php?content=v25/v0.html
- Uranus: PIA18182 https://photojournal.jpl.nasa.gov/catalog/PIA18182
- Uranus/Earth comparison table: after "The Cambridge Photographic Guide to the Planets" by F. W. Taylor (Cambridge UP, 2001), p. 268.
- Herschel: from National Air and Space Museum, Exploring the Planets: Discovering New Planets http://www.nasm.si.edu/ceps/etp/discovery/disc_planets.html
- Why Uranus is blue: from "Explorations: An Introduction to Astronomy" by Thomas T. Arny, Fig. 9.18, http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch09/0918.html
- Atmosphere and rings: picture from the Keck Telescope, from Astronomy Picture of the Day 2004 November 18 http://apod.nasa.gov/apod/ap041118.html
- Seasons: from "Uranus' magnetic forces switch 'on and off' " https://www.pbs.org/newshour/science/uranus-magnetic-forces-switch-off
- Side-on rings: Hubblesite release STScI-2005-33 http://hubblesite.org/newscenter/archive/releases/solar-system/uranus/2005/33/. Eclipse on Uranus: Hubblesite release STScI-2006-42 http://hubblesite.org/newscenter/archive/releases/solar-system/uranus/2006/42/
- Changing view of Uranus: from Imke de Pater http://astro.berkeley.edu/~imke/Infrared/UranusAo/Uranus_darkrings.htm
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- Uranus' magnetic field: from Astronomy 161, The Solar System, Lect 17 http://csep10.phys.utk.edu/astr161/lect/uranus/surface.html
- Rings: false colour image of a Voyager photo, from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/uranus/u-ring.htm
- Moon pictures: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/eng/triton.htm
- Montage of Uranus and moons: artist's impression based on Voyager images. From Smithsonian Institution: Exploring The Planets: Uranus http://www.hrw.com/science/si-science/physical/astronomy/ss/uranus/uran_moons.html
- Uranus encounter times: from "Atlas of Uranus" by Garry Hunt and Patrick Moore (Cambridge UP, 1989), p. 53
- Trajectory of Uranus encounter: from ~What do we know about Uranus' moons? Part 1" http://www.planetary.org/blogs/emily-lakdawalla/2009/1815.html
- HST image of rings and moons: from Astronomy Picture of the Day 26 November 1997 http://apod.nasa.gov/apod/ap971126.html
- Changing position of the poles: re-drawn from "Atlas of Uranus" by Garry Hunt and Patrick Moore (Cambridge UP, 1989), p. 30
- Moon images: from Voyager 2's images of Uranian moons by Ted Stryk, http://www.planetary.org/multimedia/space-images/uranus/voyager-2-s-images-of-uranian-moons.html
- Montage of Neptune and Triton: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/nep/trinep1.htm
- Adams: from "John Couch Adams and the discovery of Neptune" by A. B. Ruth, The Eagle 1997 http://www.joh.cam.ac.uk/publications/eagle97/Eagle97-John.html
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- Rings: from Voyager 2 Gallery of Neptune's Ring System http://ringmaster.arc.nasa.gov/neptune/voyager/
- Moons: from "Satellites of the outer planets" http://www.lpi.usra.edu/research/outerp/moons.html
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- Pluto and Charon: from NASA, "Charon and Pluto: Strikingly Different Worlds" https://www.nasa.gov/image-feature/charon-and-pluto-strikingly-different-worlds
- Artist's conception of Pluto and Charon: from Astronomy Picture of the Day 2001 October 18 http://apod.nasa.gov/apod/ap011018.html
- HST image of Pluto/Charon: from Astronomy Picture of the Day 13 February 1999 http://apod.nasa.gov/apod/ap990213.html
- Pluto through the years: from Olkin, Ennico.& Spencer, "The Pluto system after the New Horizons flyby", NatAst 1, 633 (2017), Fig. 1
- Pluto discovery images: from Astronomy 110 by Gareth Wynn-Williams, Lecture 9: The small planetary bodies http://www.ifa.hawaii.edu/~wynnwill/110/9_small_bodies.htm
- Pluto's orbit: from "The Cosmic Perspective" by Bennett, Donahue, Schneider and Voit, (Benjamin Cummings, 2000), http://dosxx.colorado.edu/Pluto/orbits.jpg
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- Pluto, Charon and the Earth: from https://solarsystem.nasa.gov/galleries/pluto-charon-size-compared-to-earth
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- Pluto's seasons: from http://www.planetary.org/blogs/emily-lakdawalla/2013/05021212-plutos-seasons-new-horizons.html
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- Pluto's heart: PIA19952 https://photojournal.jpl.nasa.gov/catalog/PIA19952
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- Sputnik Planitia: from http://www.slate.com/blogs/bad_astronomy/2015/09/10/pluto_new_images_from_new_horizons.html
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- Close-up of icy plains: PIA20336 https://photojournal.jpl.nasa.gov/catalog/PIA20336
- Sputnik Planitia filling impact basin: from Olkin et al. Fig. 3 https://www.nature.com/articles/s41550-017-0257-3
- Pluto's orientation with Sputnik Planitia: from Keane et al., "Reorientation and faulting of Pluto due to volatile loading within Sputnik Planitia", Nature 540, 90-93 (2016)
- Sub-surface ocean: from Olkin et al. https://www.nature.com/articles/s41550-017-0257-3

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