

Modern Astronomy: Voyage to the Planets

Lecture 8

The outer solar system: Uranus, Neptune and (minor) planets beyond

University of Sydney
Centre for Continuing Education
Spring 2011

Tonight:

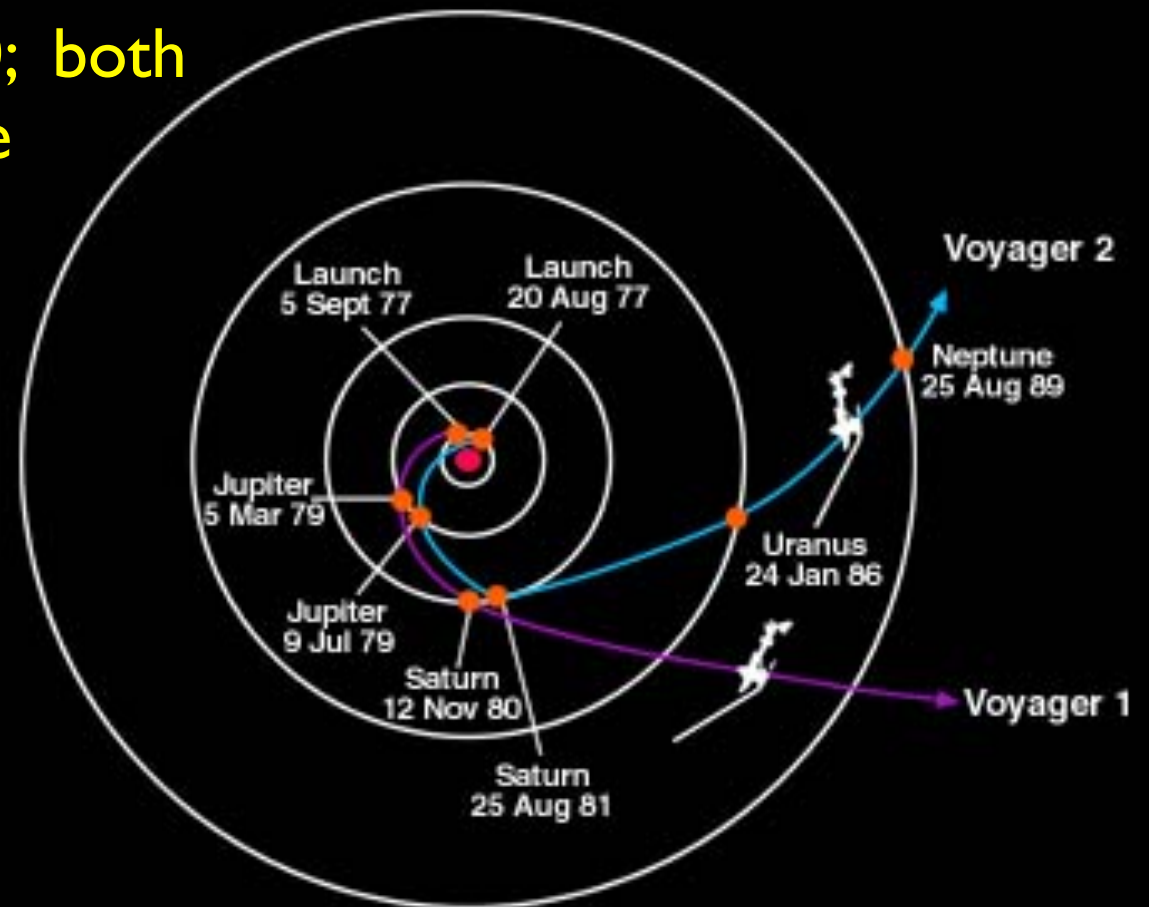
- Uranus
- Neptune
- Pluto and Charon
- Eris, and beyond



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.



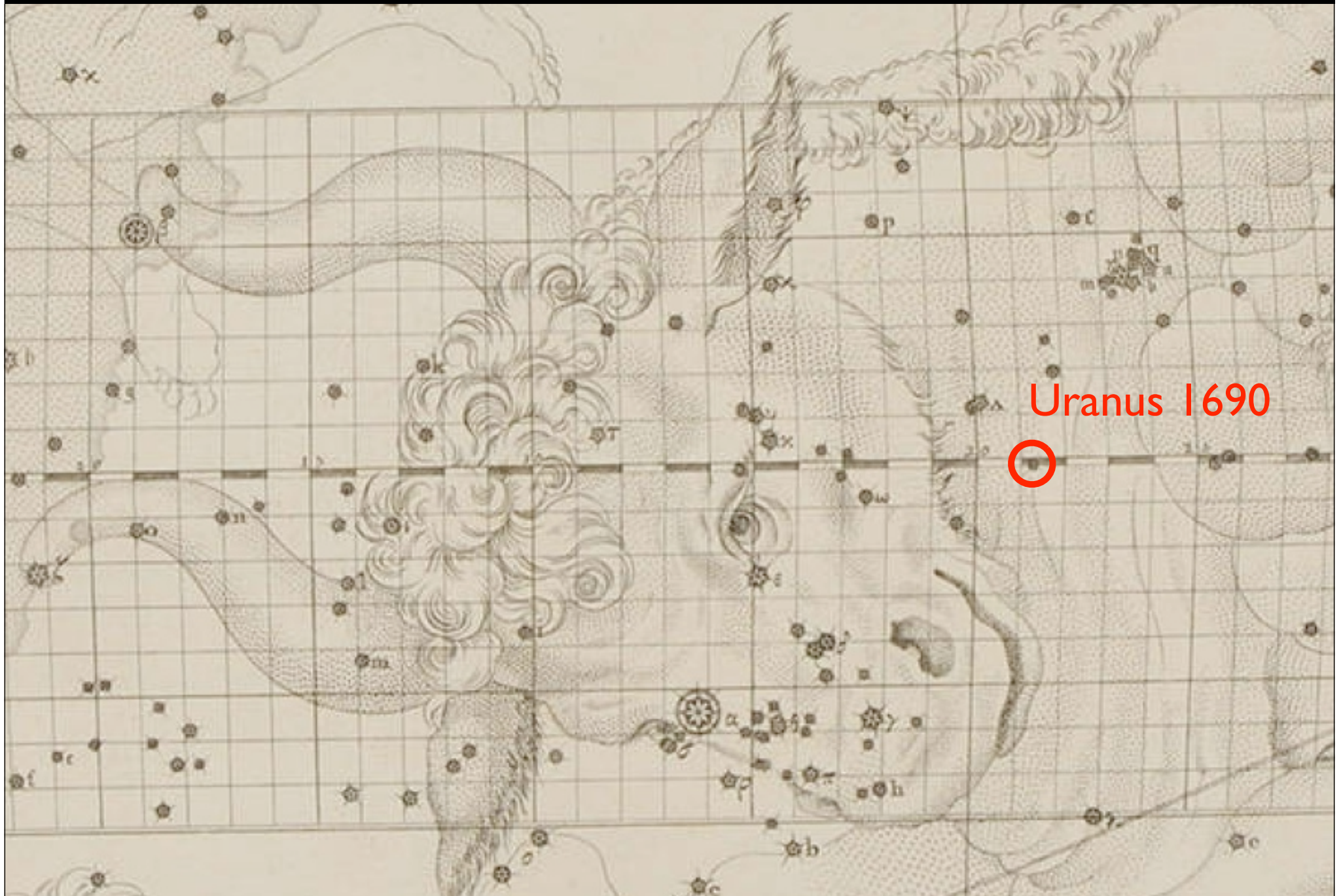
Uranus



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



Basic facts



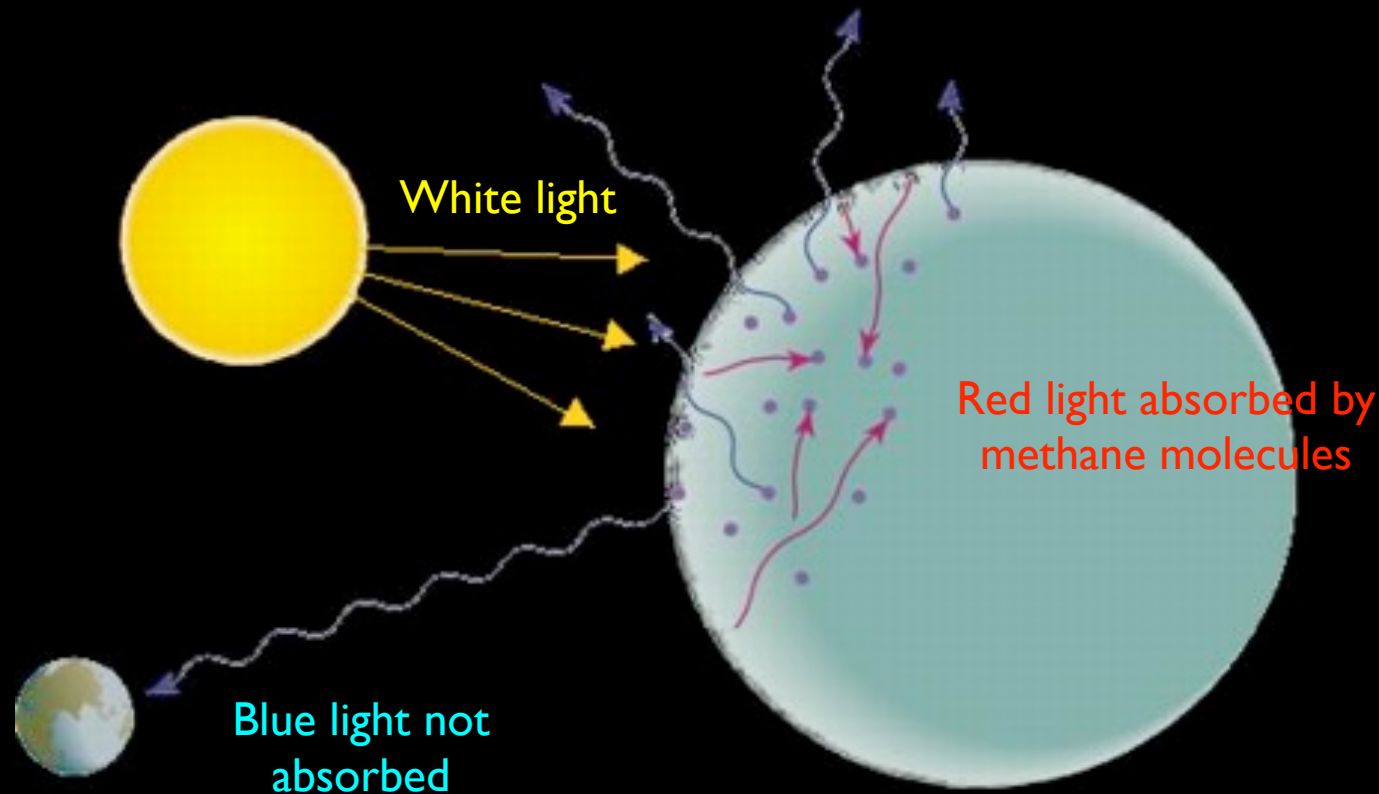
	Uranus	Uranus/Earth
Mass	$86.83 \times 10^{24} \text{ kg}$	14.536
Radius	25,559 km	4.007
Mean density	1.270 g/cm^3	0.230
Gravity (eq., 1 bar)	8.87 m/s^2	0.905
Semi-major axis	$2872 \times 10^6 \text{ km}$	19.20
Period	30 685.4 d	84.011
Orbital inclination	0.772°	-
Orbital eccentricity	0.0457	2.737
Axial tilt	97.8°	4.173
Rotation period	-17.24 h	0.720
Length of day	17.24 h	0.718

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

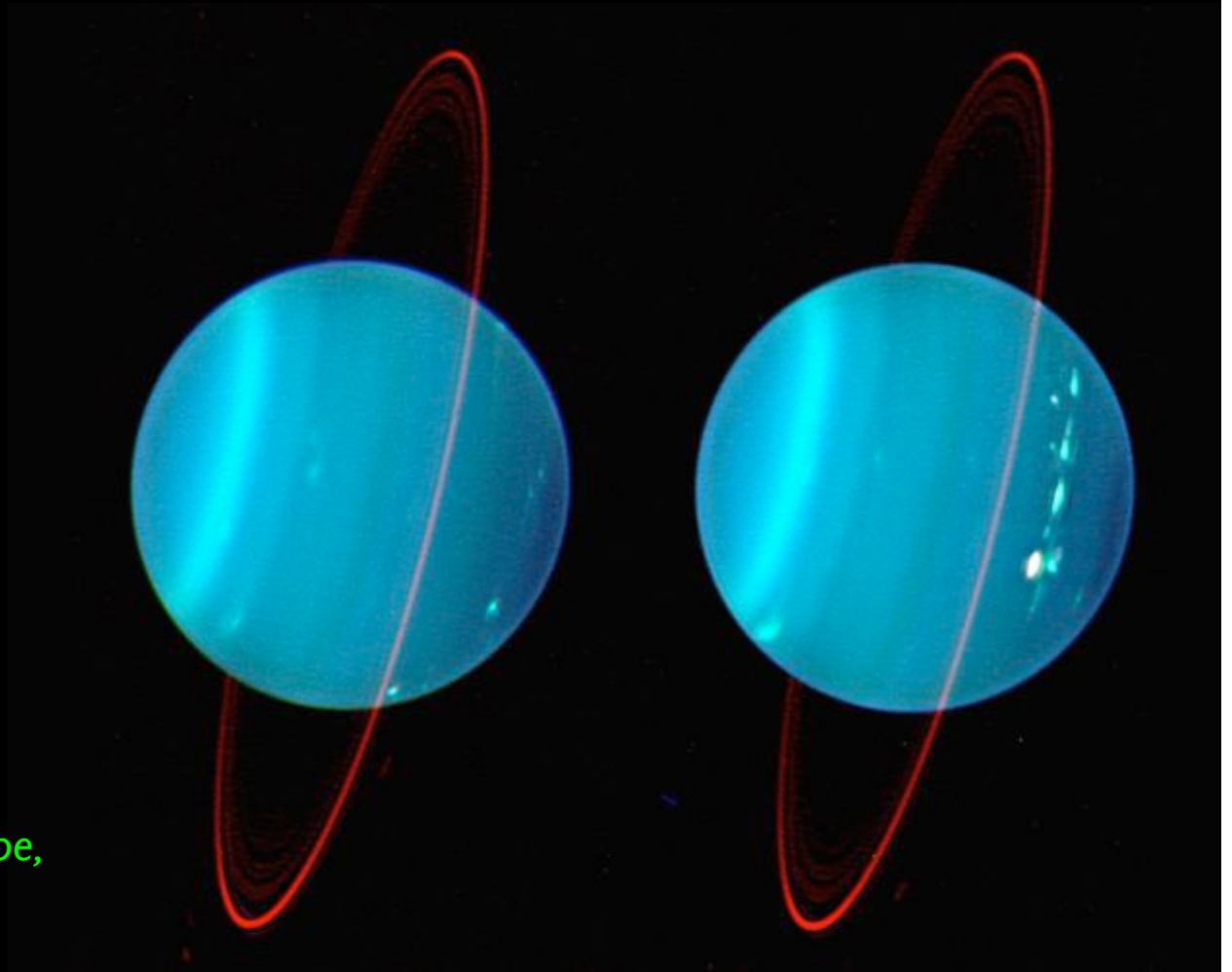
Uranus does not have as much internal heat as Jupiter or Saturn, so the convection currents in the atmosphere are not as strong. This explains why Uranus lacks clear bands.



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.

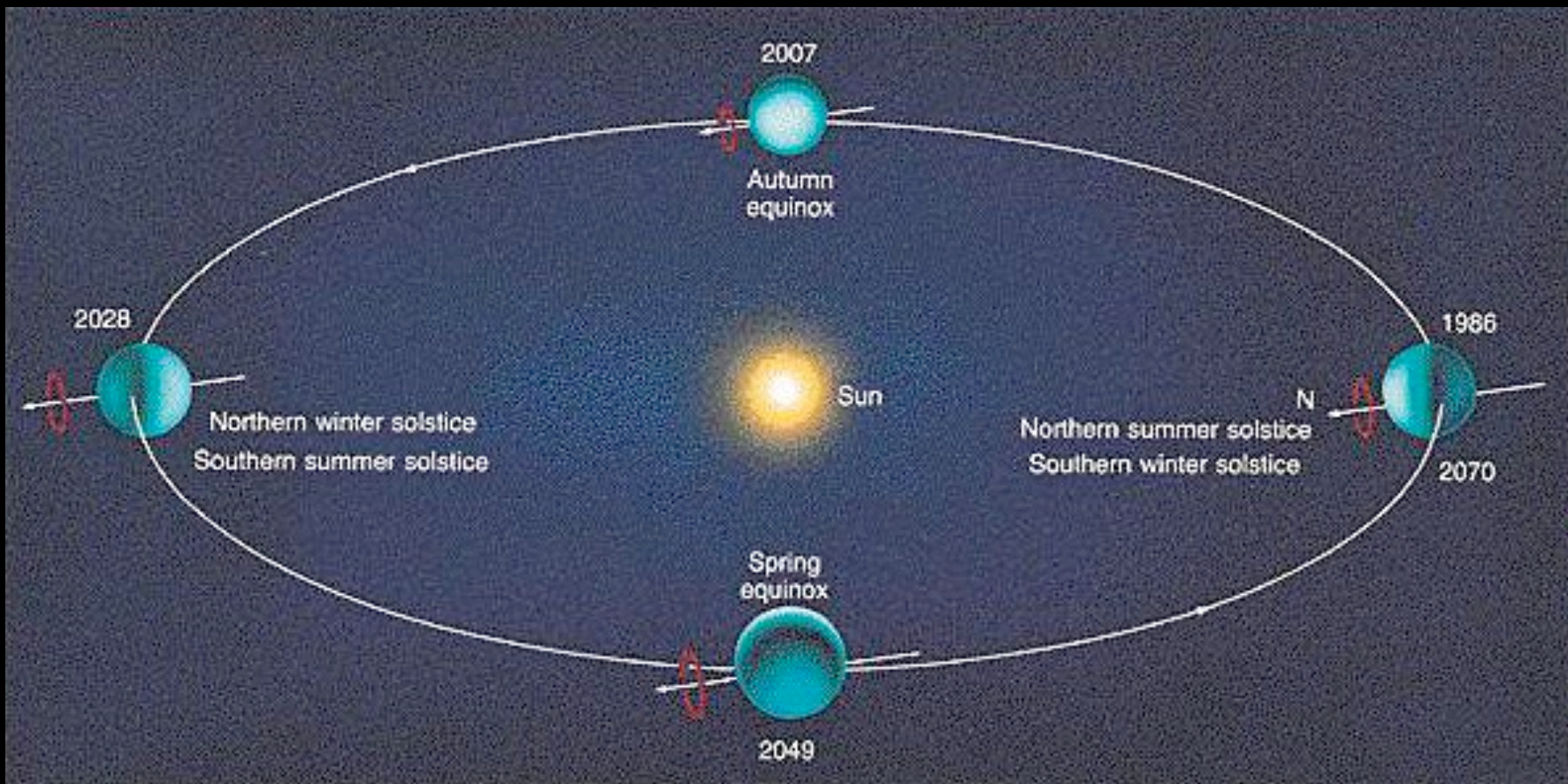


Unlike all the other planets, the rotation axis of Uranus is tilted to lie almost in the plane of its orbit. The equatorial plane is inclined 98° , so it spins *backwards* compared to other planets.



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.

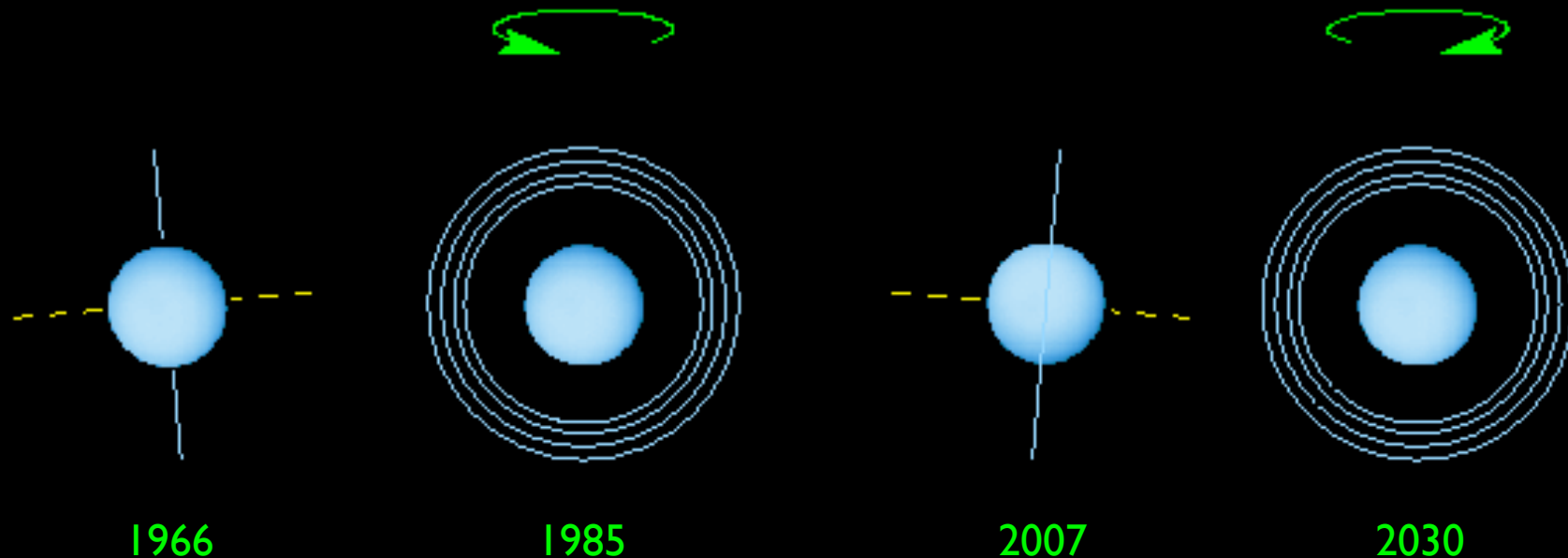


The Hubble Space Telescope saw enormous storms swirling around Uranus as the northern hemisphere came out of its 20-year winter.

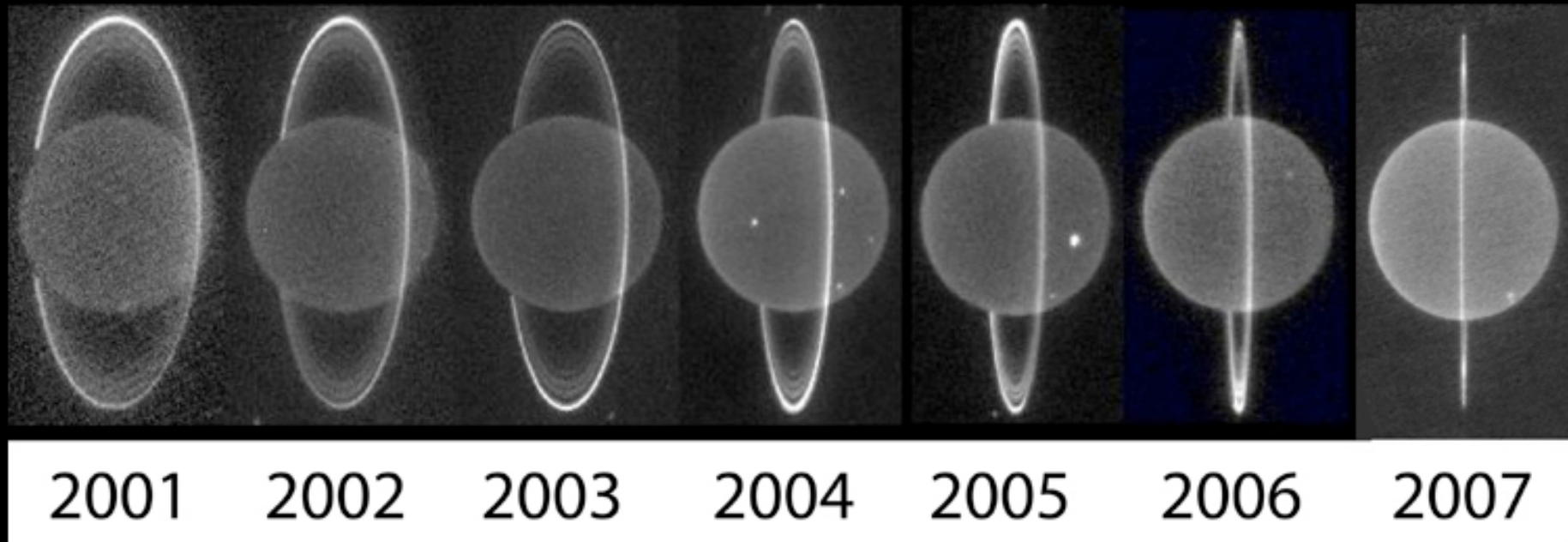
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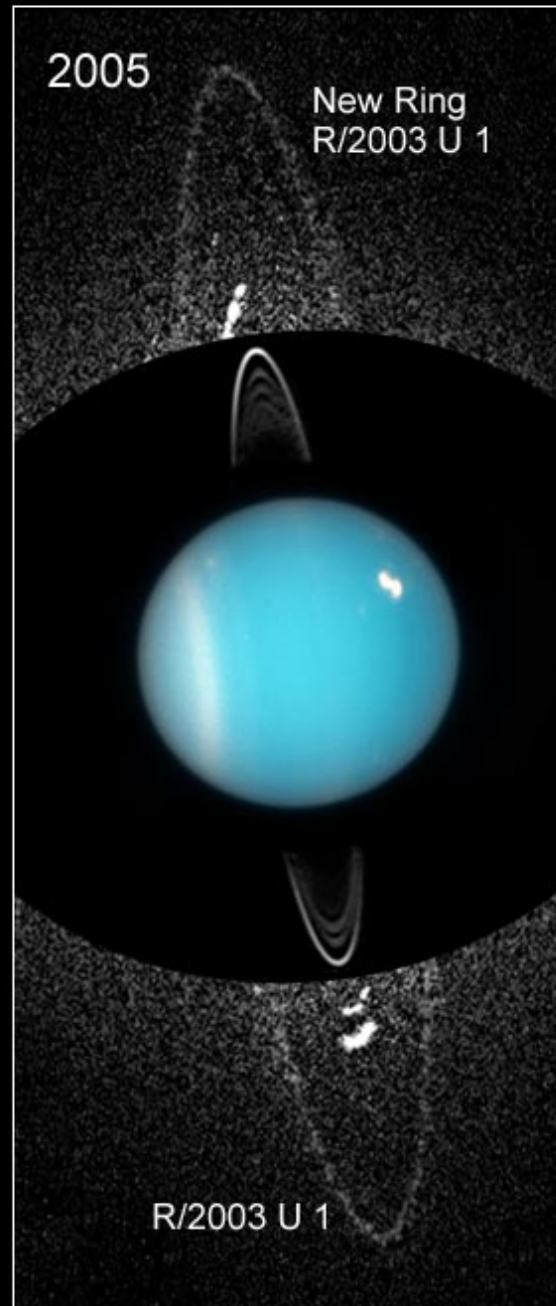
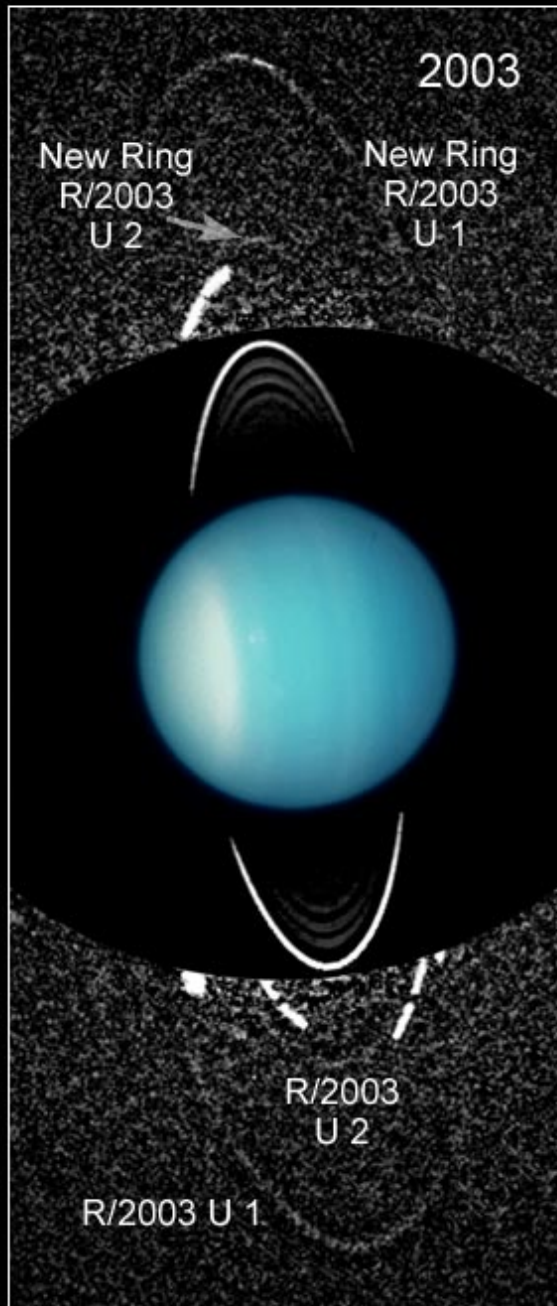
Since the axis of rotation always points to the same direction in space, at some points in its orbit its pole is pointed towards us, and sometimes it appears side-on to us. Uranus' equinox occurred in December 2007, at which time we saw Uranus' rings and moons side-on.



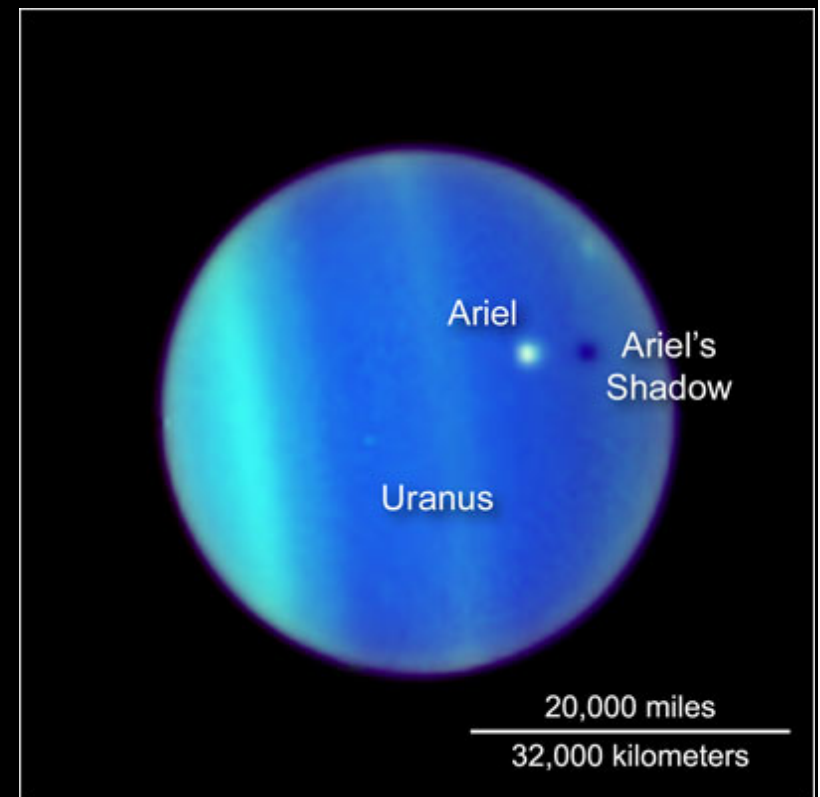
The changing view of Uranus since 2000, from Keck. As Uranus moved to present a more edge-on view of its rings, the rings became brighter and more distinct



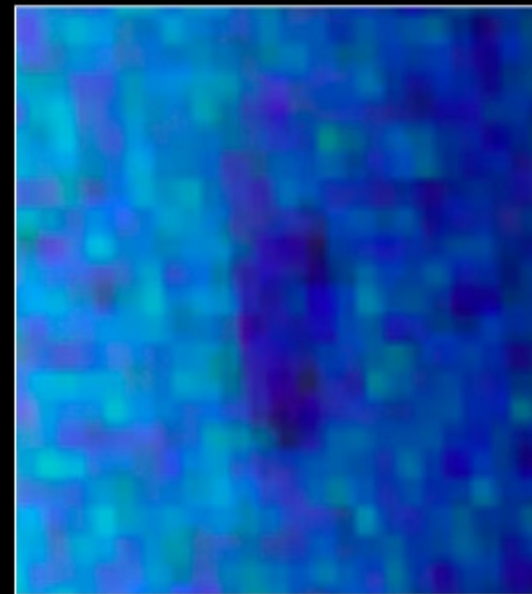
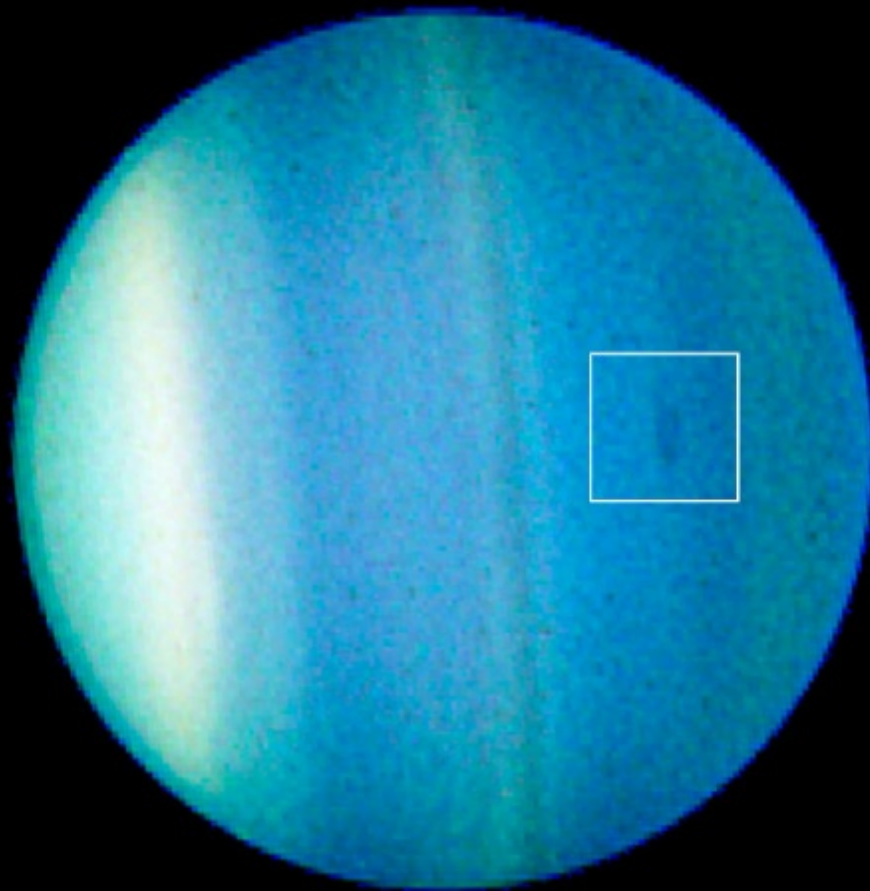
Uranus ■ HST ACS/HRC



HST images of Uranus, showing the moon/ring plane becoming steadily more side-on to us. The image below is from 2006, and shows an eclipse of Uranus by Ariel.



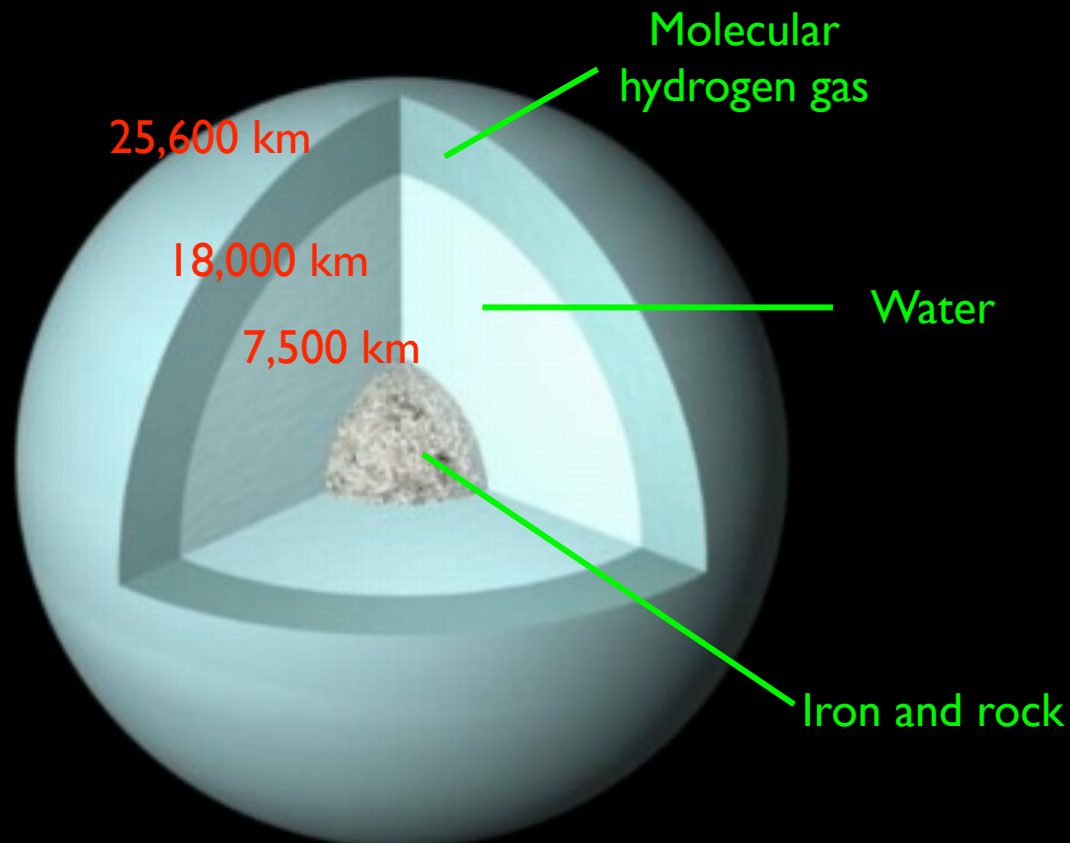
As Uranus approached equinox, its cloud features became more pronounced. It appears that Uranus' extreme axial tilt also results in extreme seasonal variations in its weather.



Hubble image of a dark cloud in Uranus' atmosphere in 2006.

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

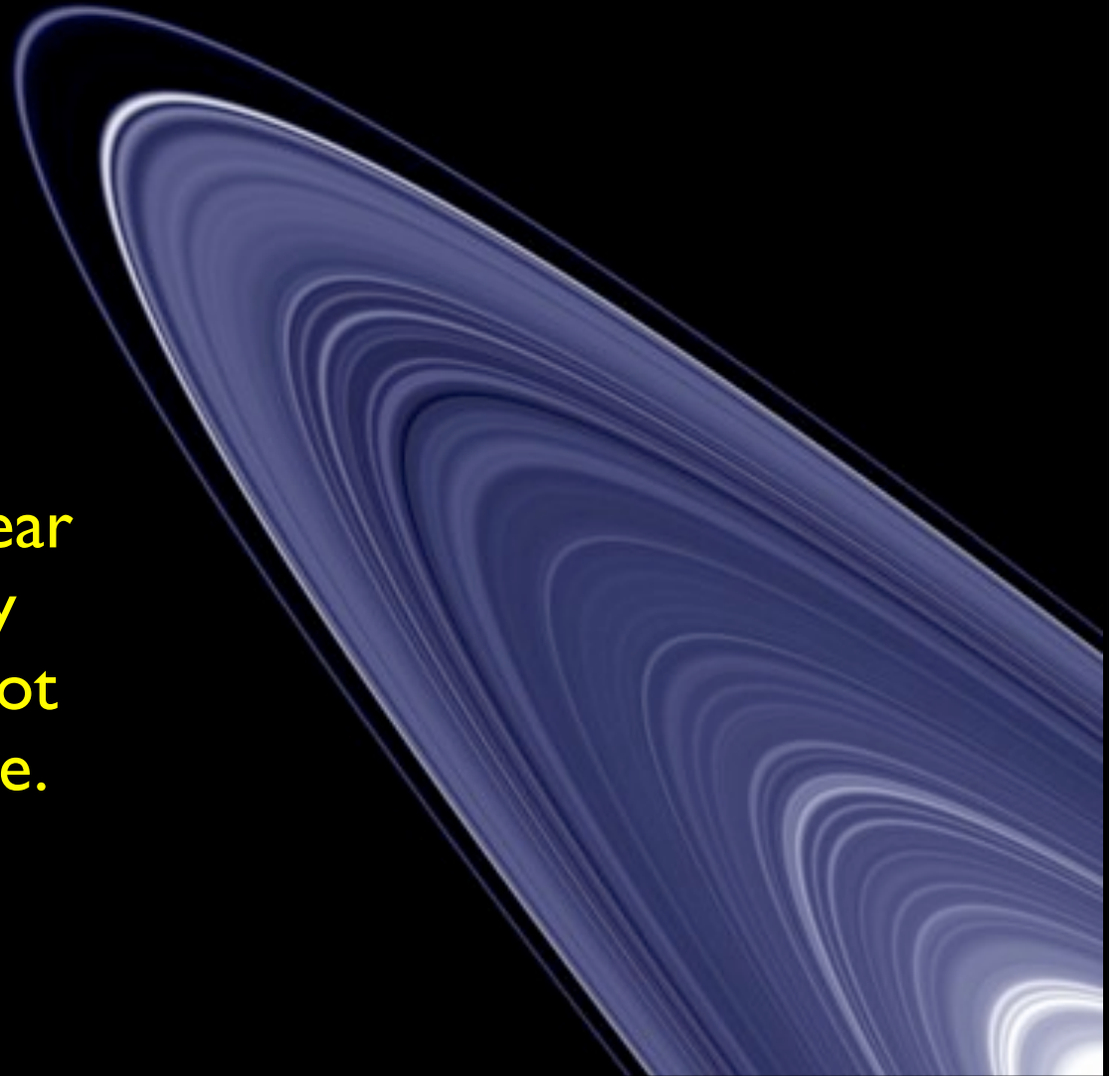
mantle made up mostly of water with some methane and ammonia. The inner core is about 1 Earth mass, and the outer layer is a hydrogen and helium-rich atmosphere.



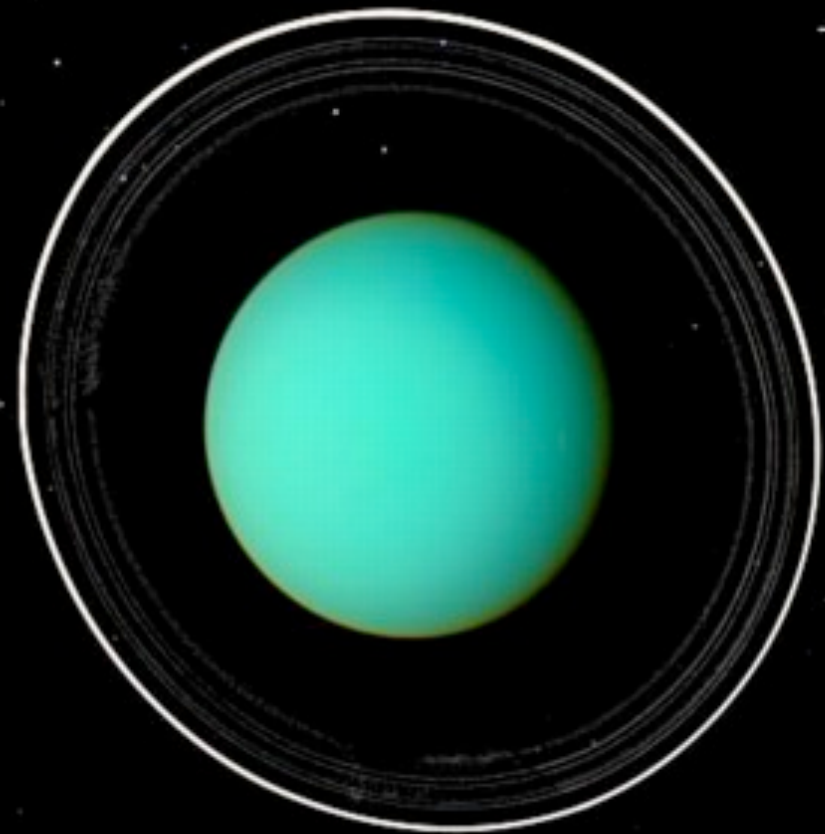
Uranus has a magnetic field, about 50 times as strong as Earth's. However, the magnetic axis is not only tilted by about 60 degrees from the rotational axis, but is also offset from the centre of the planet by about 8000 km. This field probably arises as a result of electrical currents in the liquid mantle.



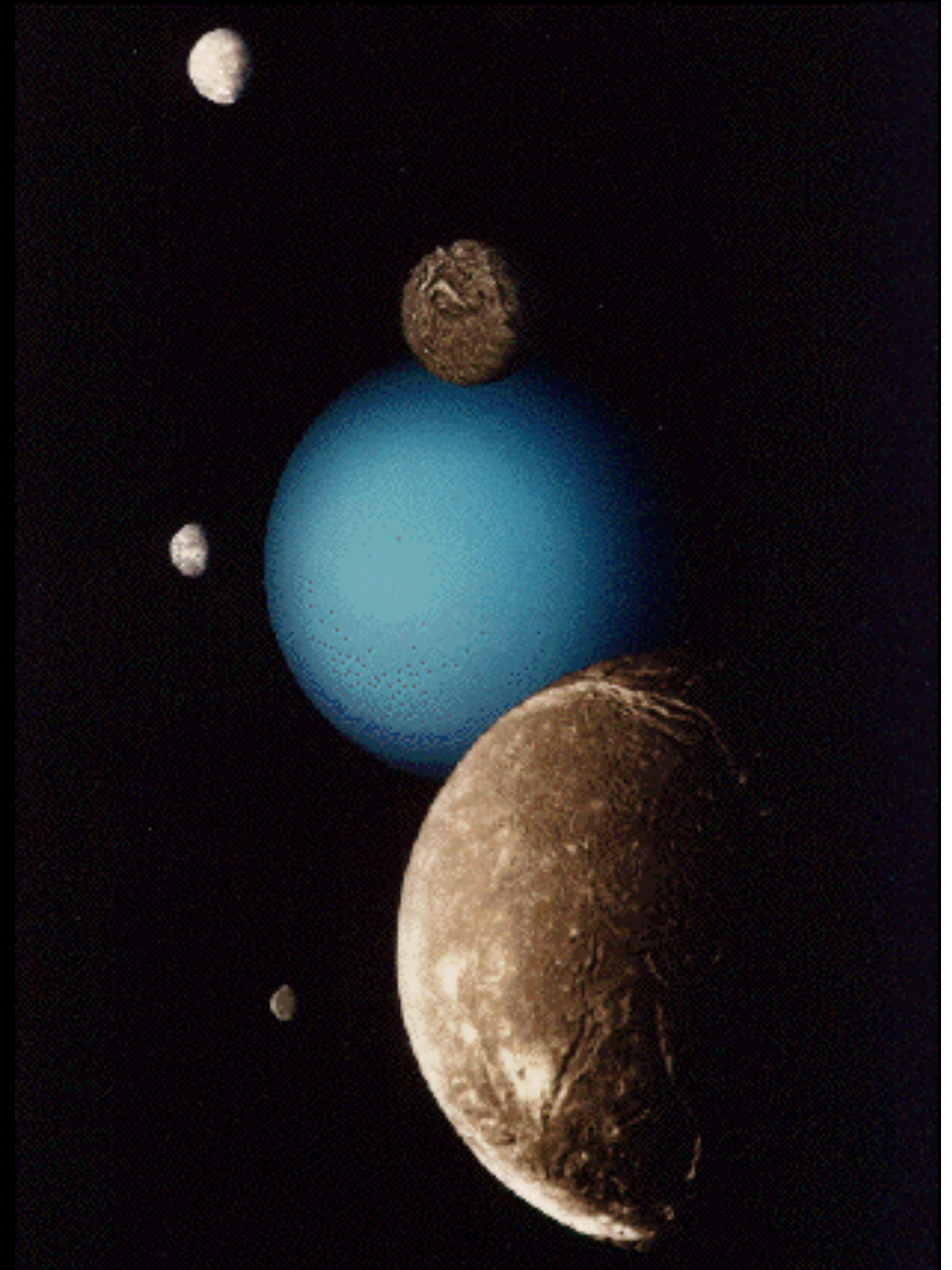
Uranus has rings which are narrow, widely separated, and eccentric, quite unlike those of Jupiter or Saturn. Most of them are less than 10 km in width. Unlike the icy rings of Saturn or the dusty rings of Jupiter, the particles in Uranus' rings are extremely dark, with albedos of only 2%, as dark as the blackest asteroids and meteorites known. The rings also appear to be clumpy, implying they are very young and have not yet reached their final state.



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.

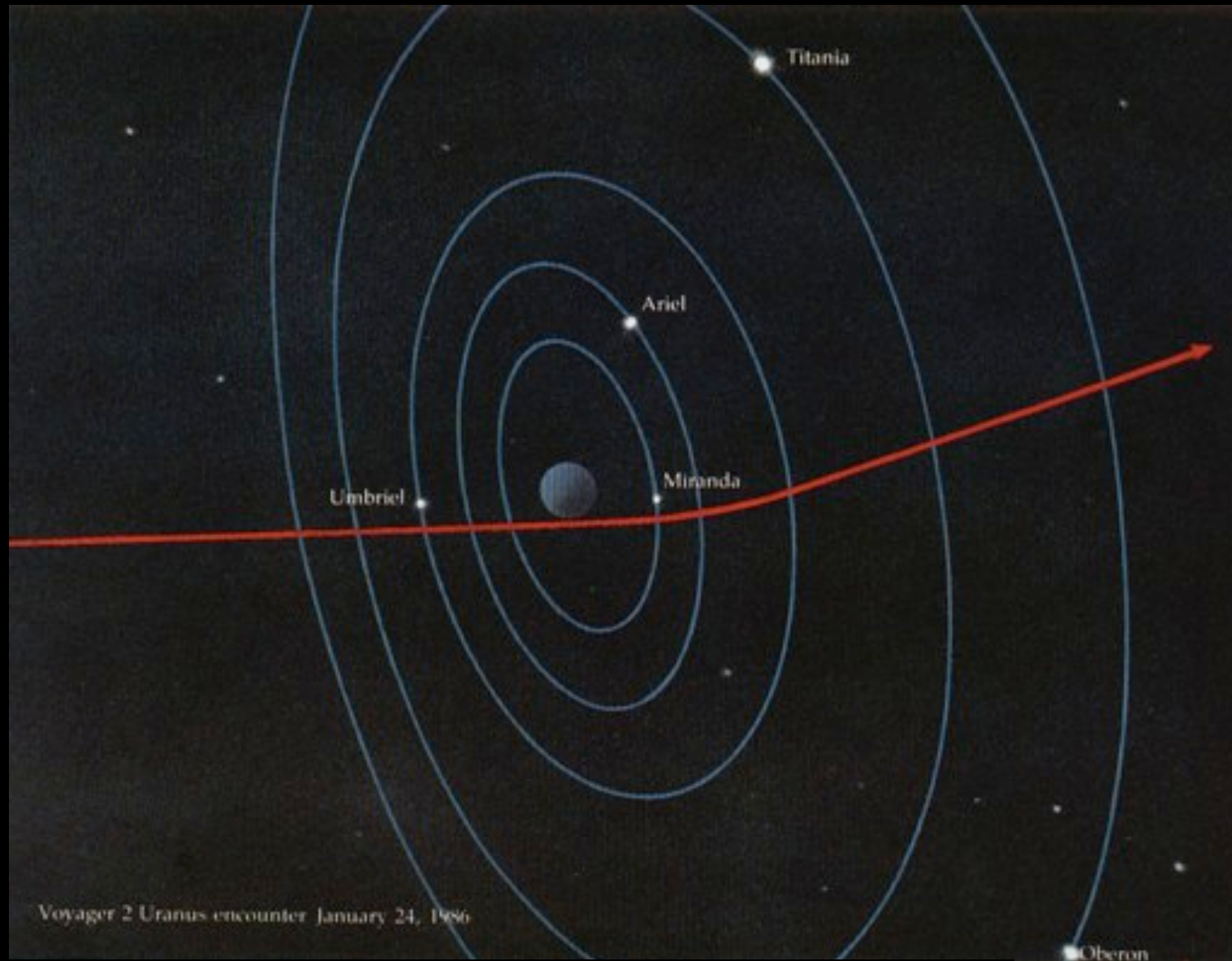


On the day of the encounter, Voyager's timetable was as follows:

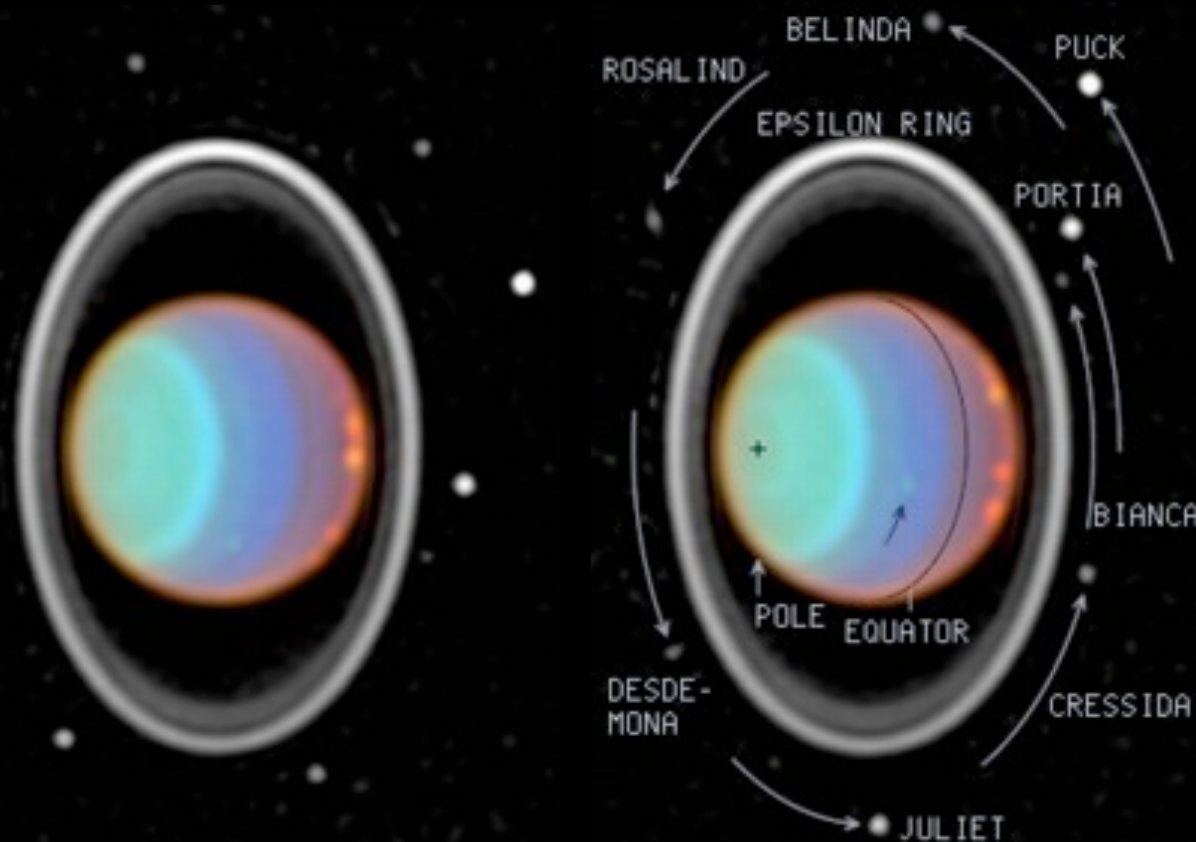
14:00	Voyager 230 000 km or 10 Uranian radii from Uranus
15:08	Closest to Titania (365 000 km)
16:12	Closest to Oberon (471 000 km)
16:20	Closest to Ariel (130 000 km)
17:03	Closest to Miranda (32 000 km)
17:16	Ring-plane crossing
17:59	Closest to Oberon (471 000 km)
20:38	Occultation of Voyager by Uranus (till 22:45)
20:45	Closest to Umbriel (325 000 km)
24:00	Voyager now 650 000 km from Uranus



Here's a picture of Voyager's trajectory during the fly-by:

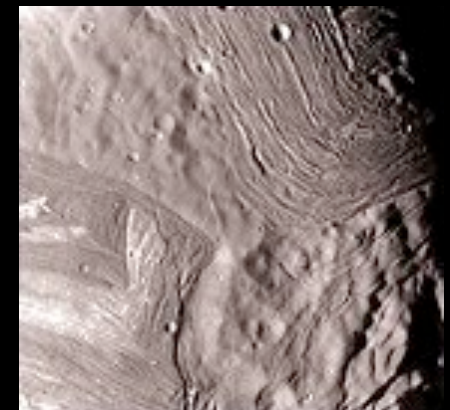


The moons are in Uranus' orbital plane, like other planets: so unlike Jupiter's moons, which appear always in a line to us, during the past two decades we were able to see Uranus' moons (nearly) face on.



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

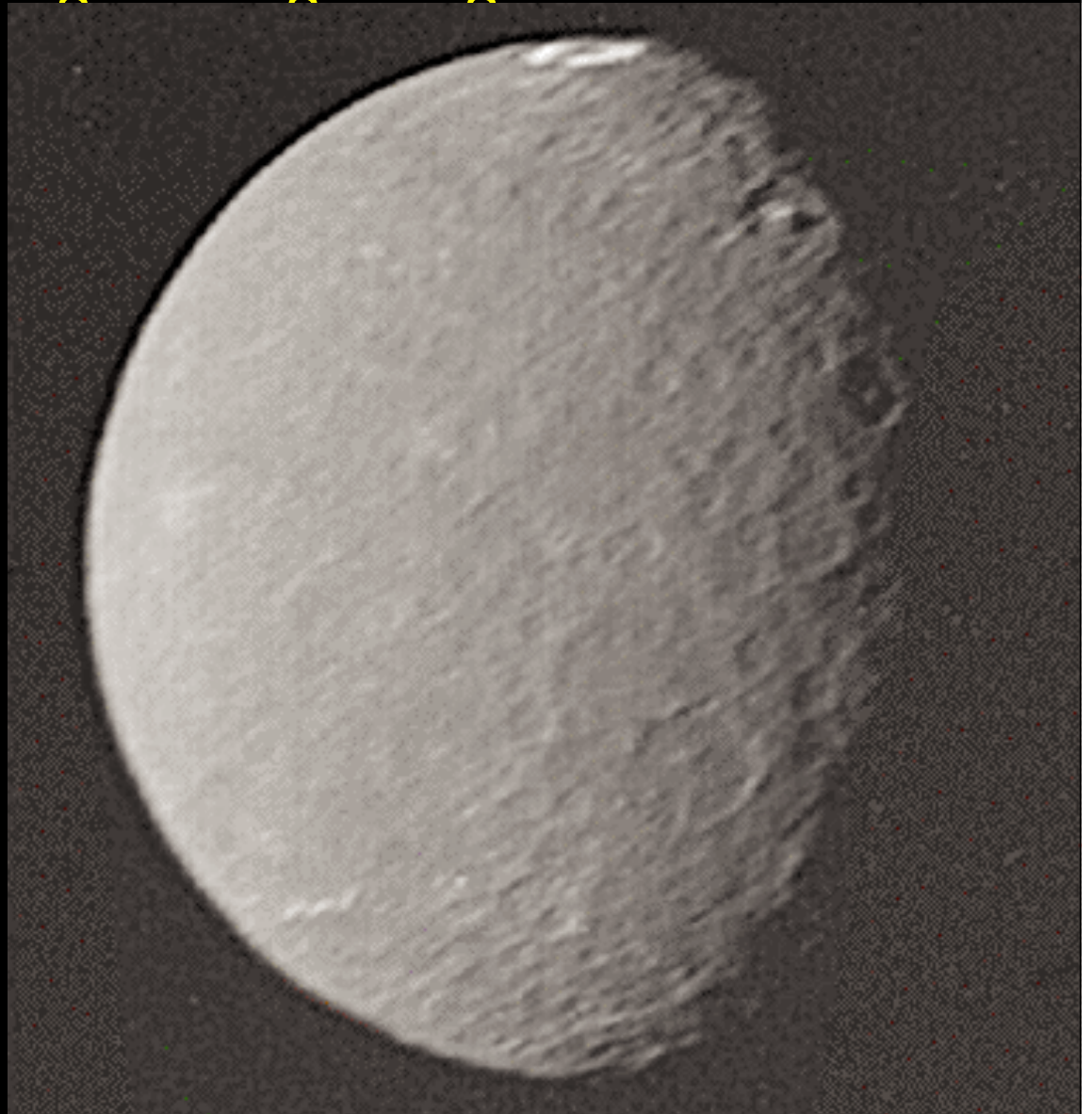
Miranda, the innermost of the five large moons, is only 470 km in diameter. Its surface looks as though it has been broken up and reassembled. It has huge fault canyons 20 km deep, layering and terraces, and old, pock-marked surfaces and young, bright regions. This suggests ice was melted and re-froze, 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.



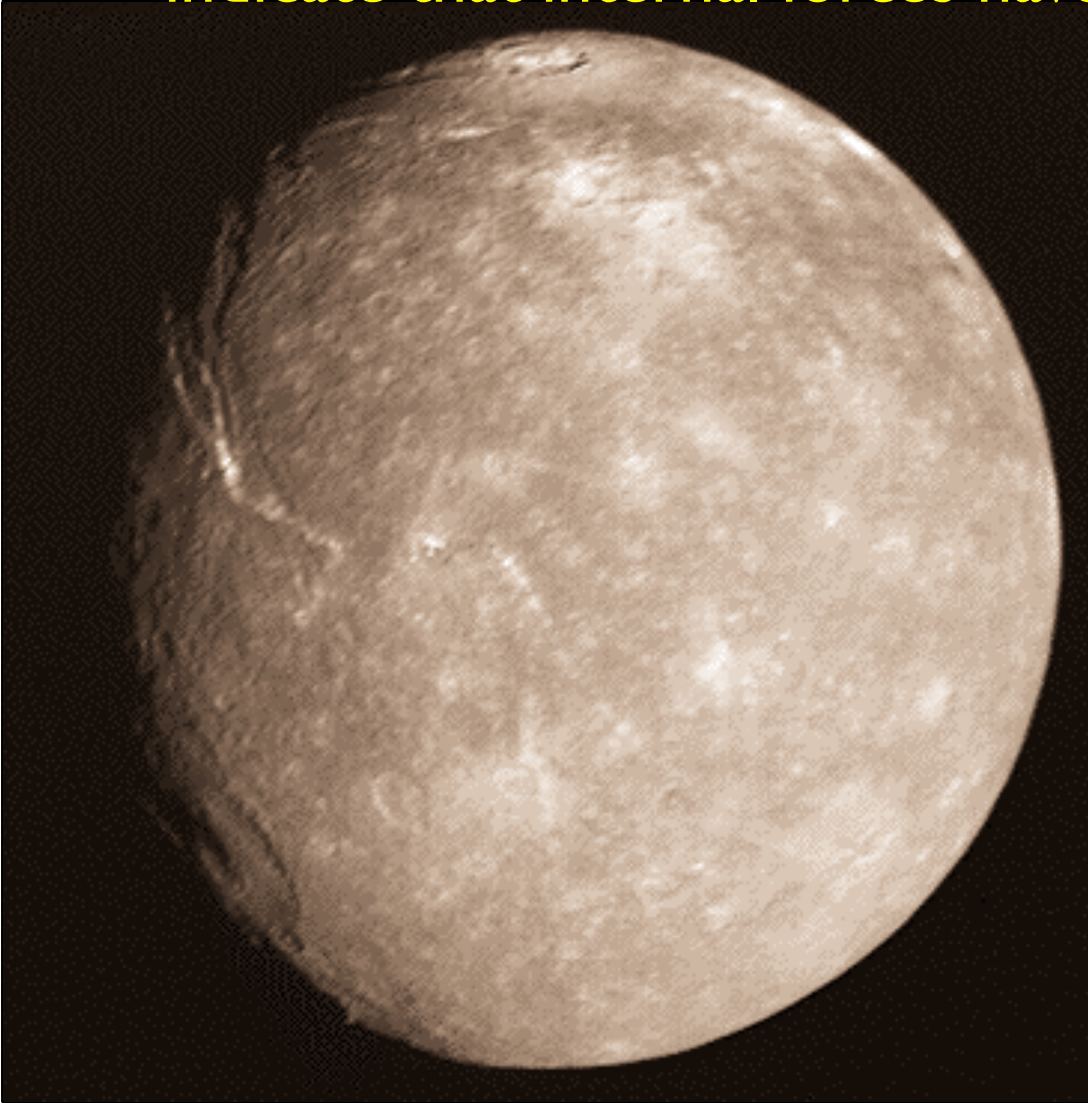
Ariel is covered with huge canyons, which look like faults produced by expansion and stretching of the crust. Some of the canyon floors appear to have been smoothed by liquid, presumably ammonia, methane or even carbon monoxide. Much of the surface is marked by small, young craters (from their bright 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.

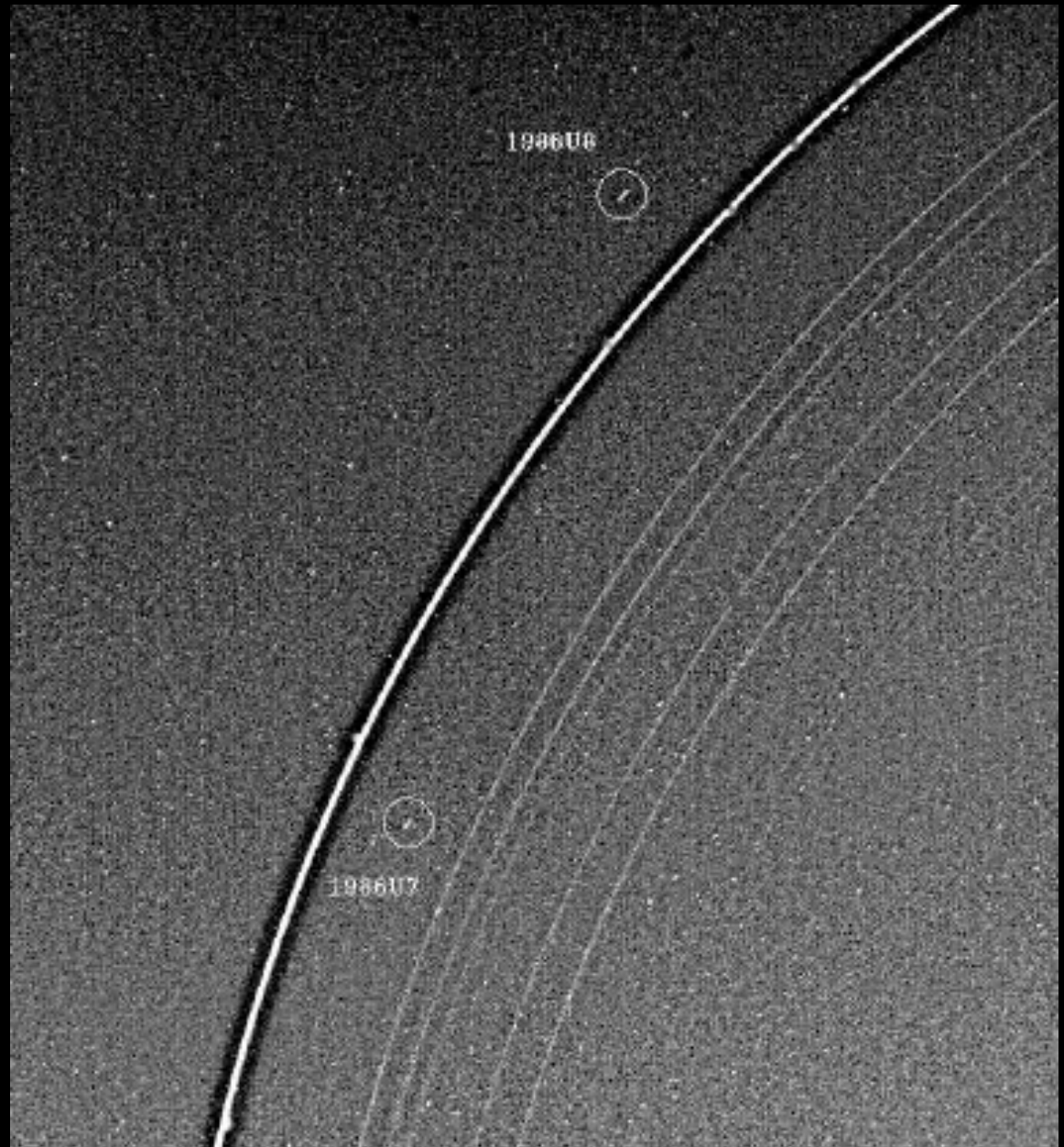


Oberon appears quite similar to Umbriel, though Oberon is 35% larger. Its surface is heavily cratered, showing more and larger craters than Ariel and Titania, some with bright rays of ejecta. Some of the crater floors are dark, perhaps covered with darker material that upwelled into the crater.

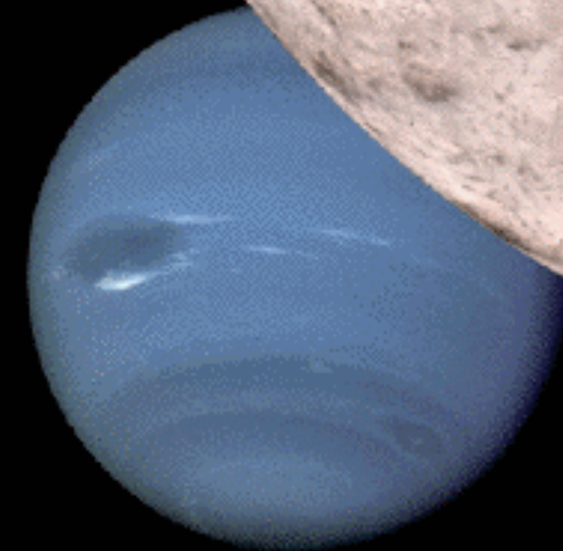
Large faults cut across the entire southern hemisphere, which indicates some geologic activity early in Oberon's history. The large crater is called Hamlet (200 km in diameter). The mountain on the limb rises 6 km above its surrounds.



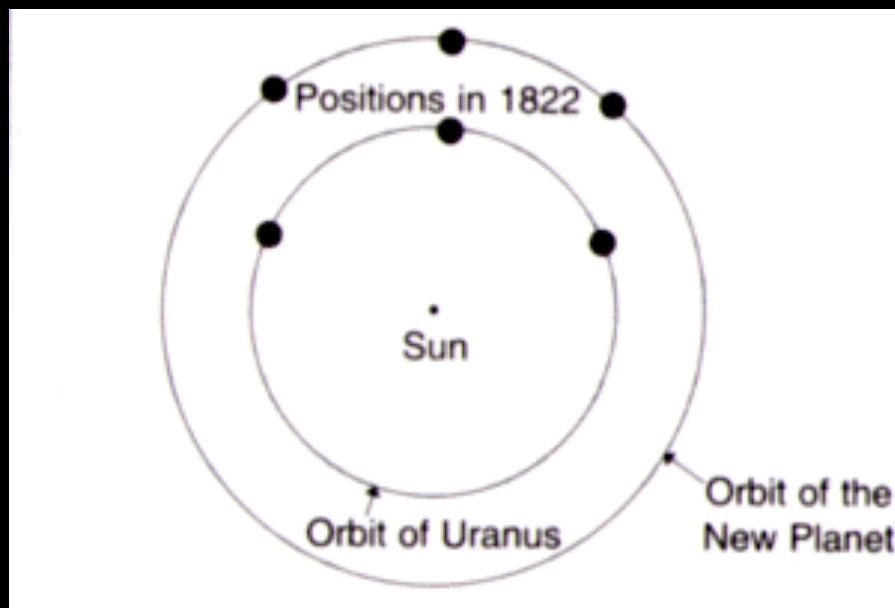
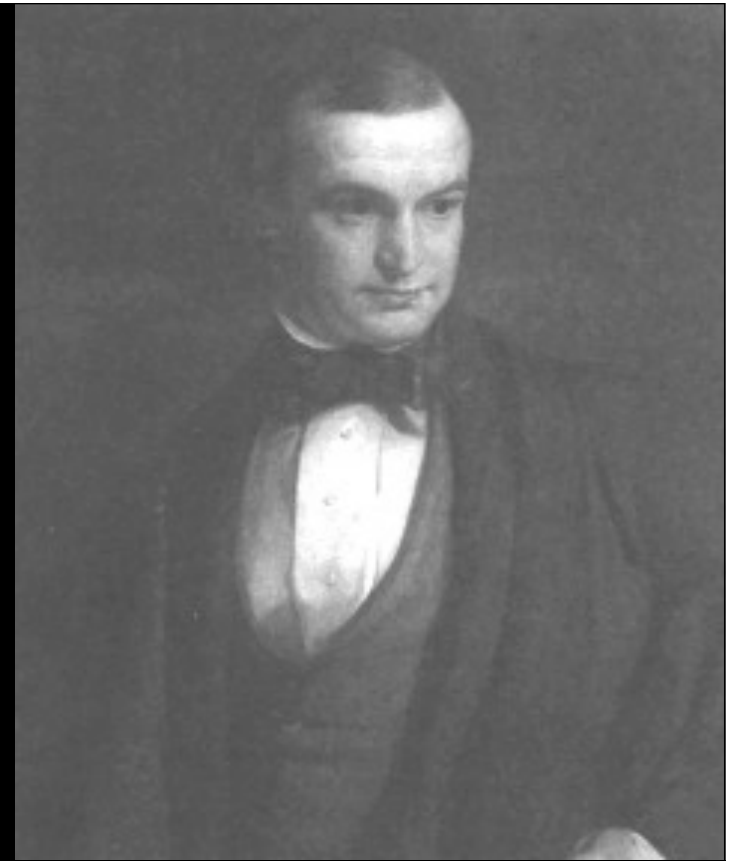
Of the ten small satellites which Voyager discovered, Cordelia and Ophelia appear to be the shepherding satellites for the bright Epsilon ring.



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.

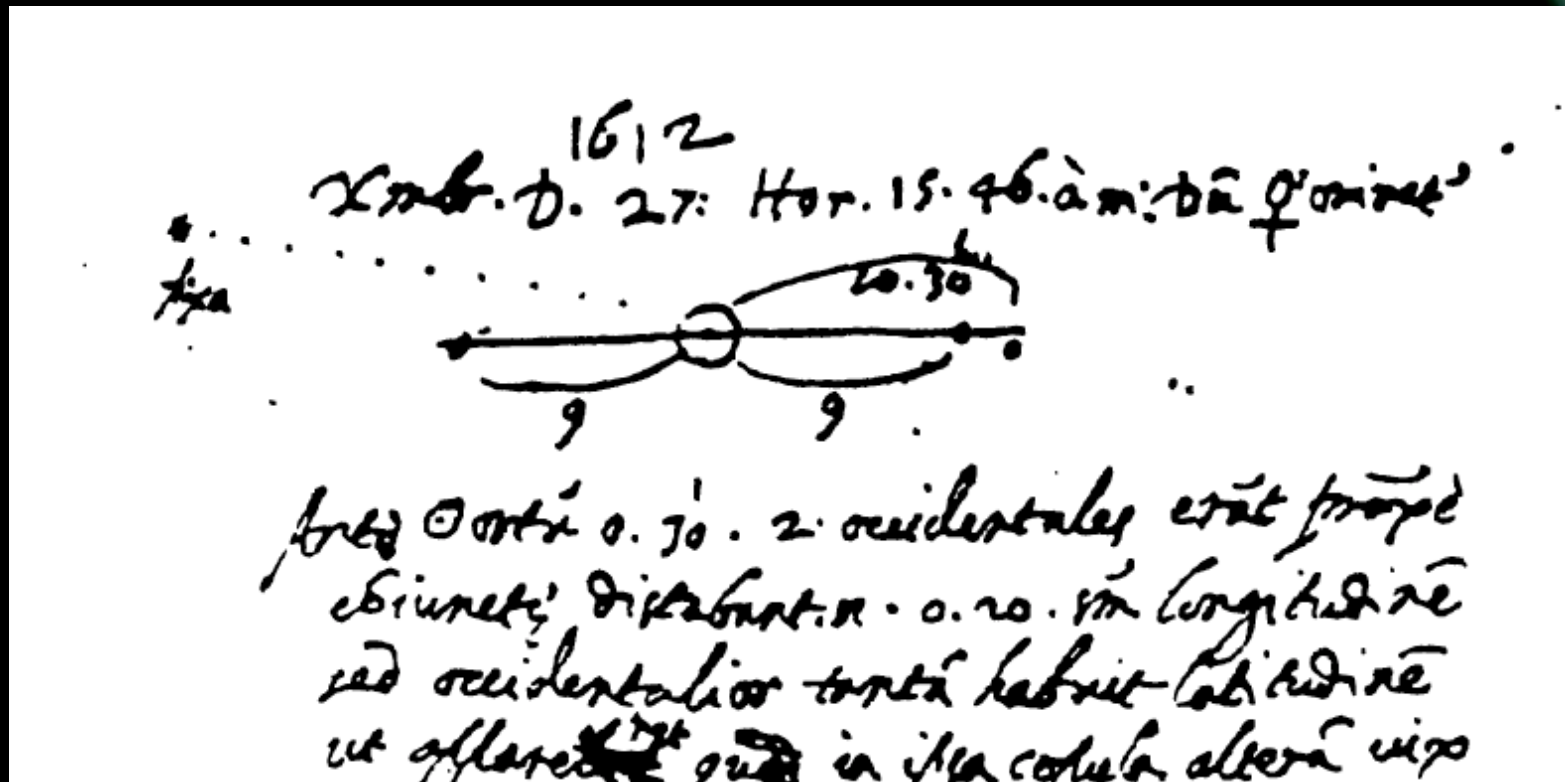
Neptune was discovered by Johann Galle in 1846, leading to an international dispute over priority.

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



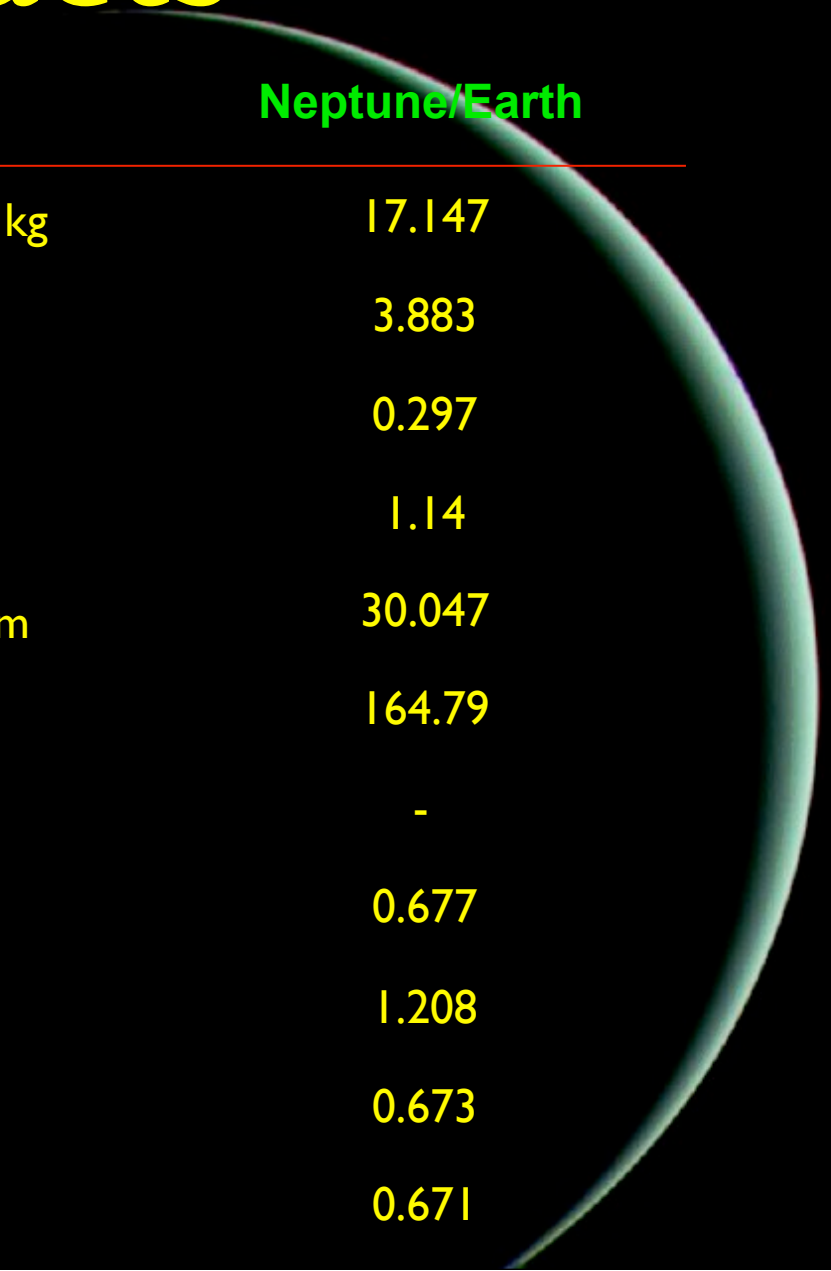
Comparison between Adams' and Leverrier's predicted positions for Neptune, and where it was found.

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!



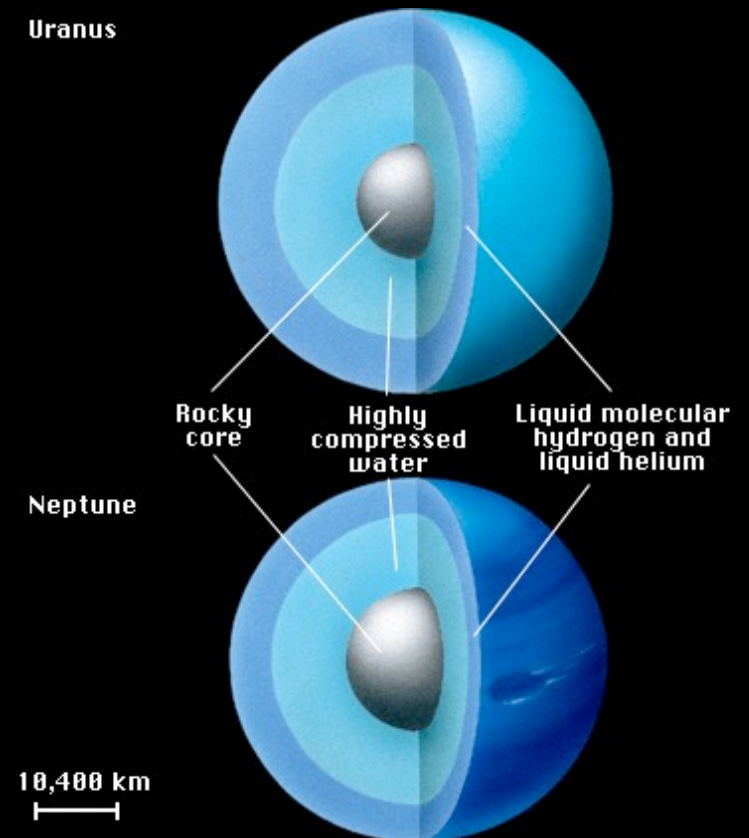
Galileo's notebook from 27th December 1612, showing Jupiter and its satellites, plus a "fixed star" which is actually Neptune (from Standish & Nobili, 1997)

Basic facts

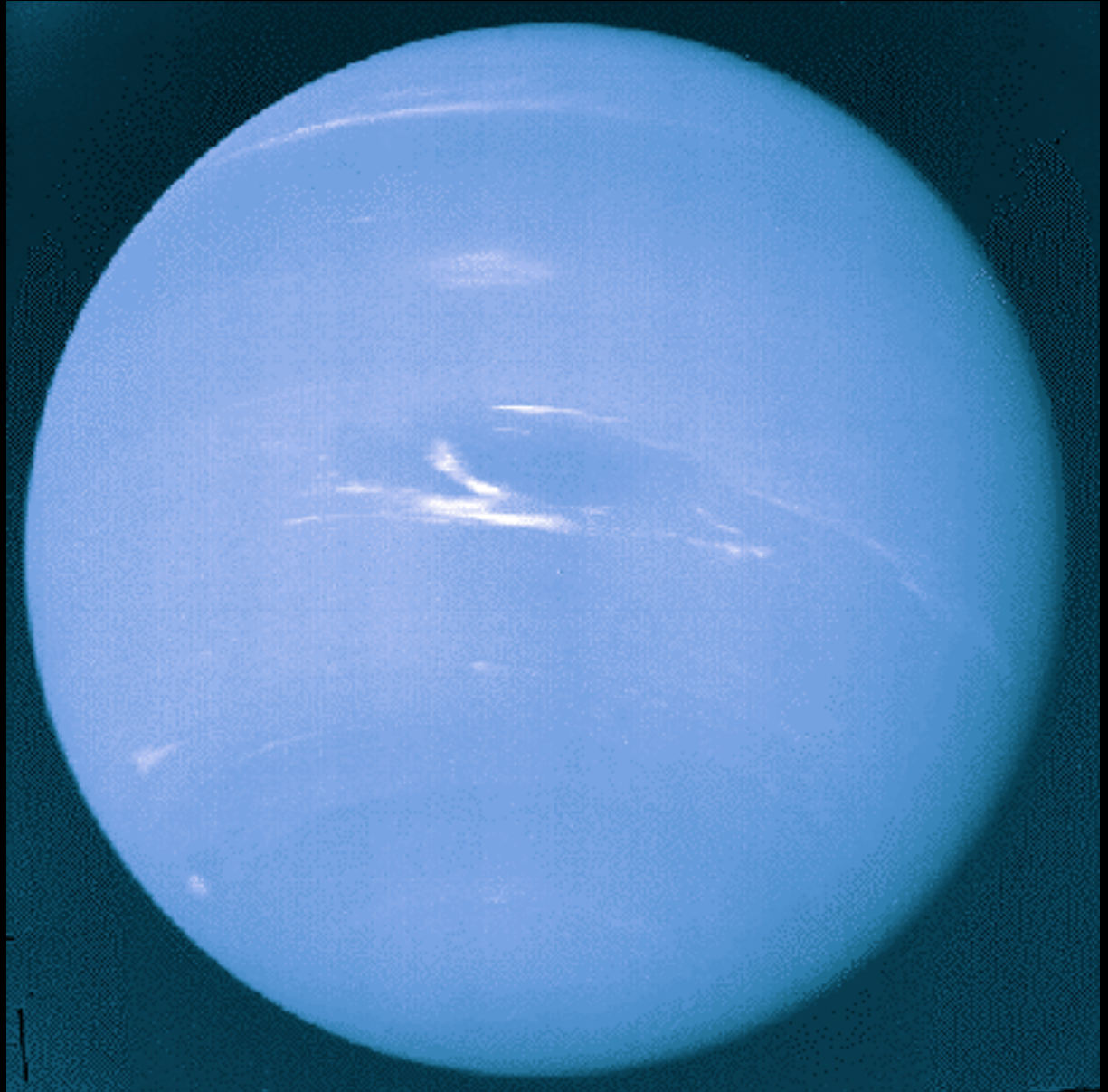


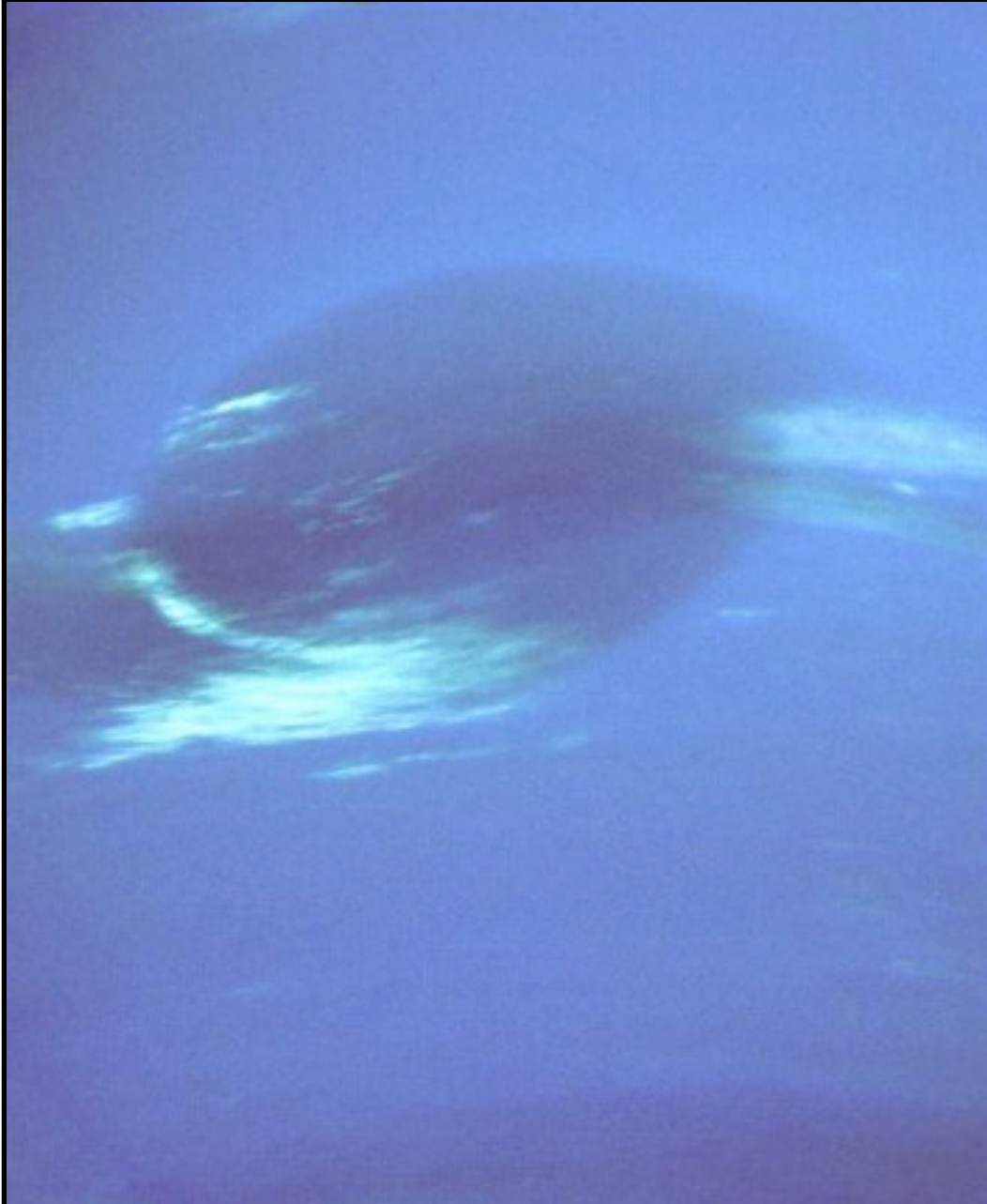
	Neptune	Neptune/Earth
Mass	$102.43 \times 10^{24} \text{ kg}$	17.147
Radius	24,764 km	3.883
Mean density	1.638 g/cm^3	0.297
Gravity (eq., 1 bar)	11.15 m/s^2	1.14
Semi-major axis	$4495 \times 10^6 \text{ km}$	30.047
Period	60 189 d	164.79
Orbital inclination	1.769°	-
Orbital eccentricity	0.0113	0.677
Axial tilt	28.3°	1.208
Rotation period	16.11 h	0.673
Length of day	16.11 h	0.671

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.



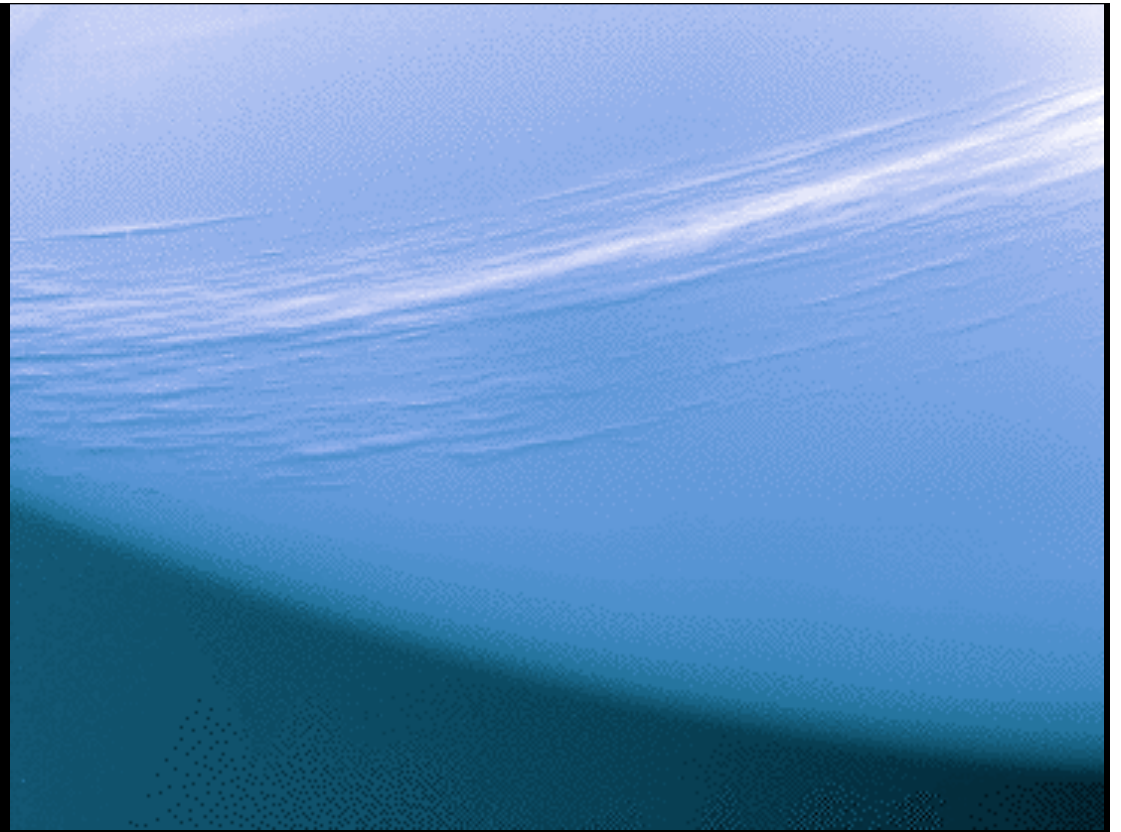
Neptune's outer surface is far more interesting than Uranus'. Its upper atmosphere is cold enough for methane (and possibly nitrogen) to condense, which form high clouds. These show up vividly in photos and reveal the rapid winds and huge storms on the planet.





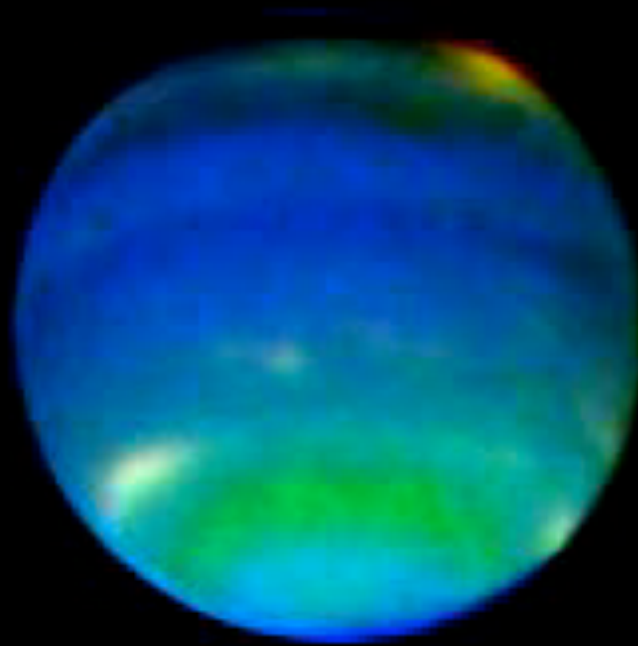
Voyager found a storm as large as the Earth, called the Great Dark Spot, about half the size of Jupiter's Great Red Spot. However, by the time Hubble imaged Neptune in 1994, the Dark Spot had vanished, so it was not nearly as long-lived as its Jovian cousin.

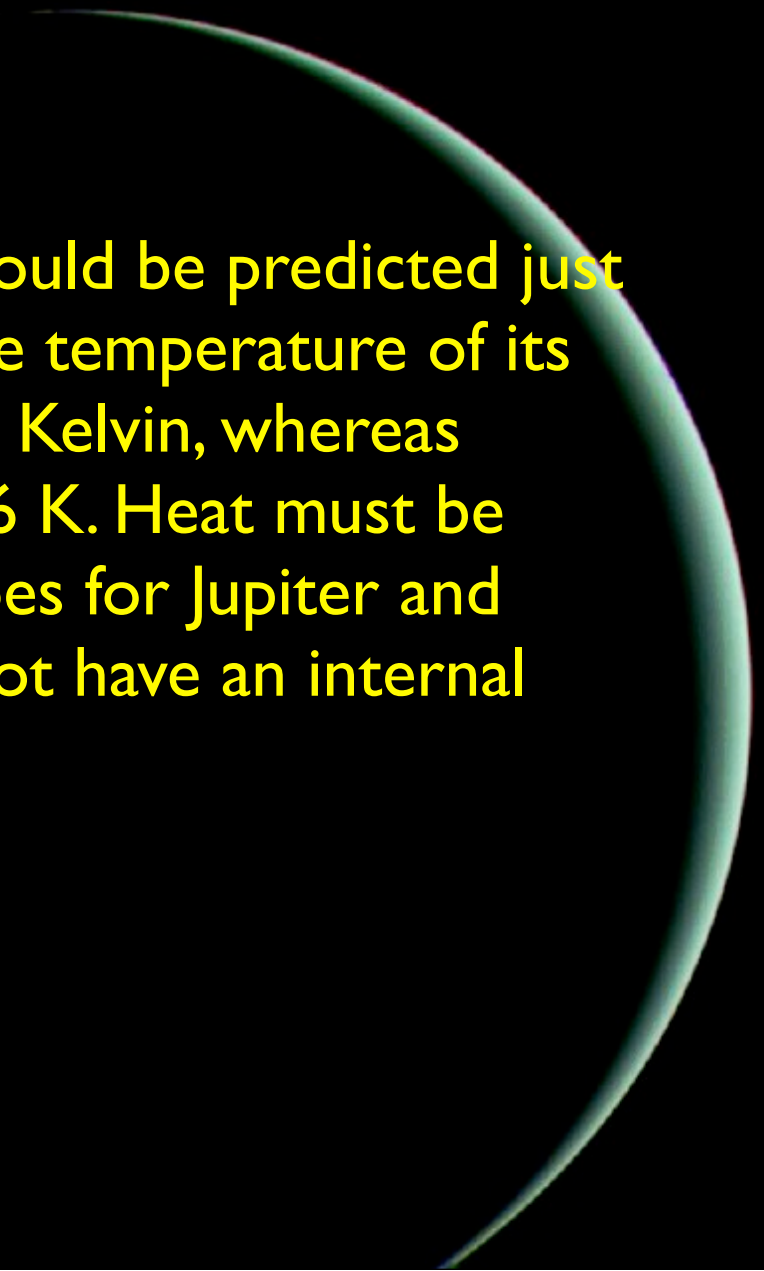
Long, bright clouds like cirrus were seen high in Neptune's atmosphere, casting shadows on the blue cloud deck 50 km below.



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.



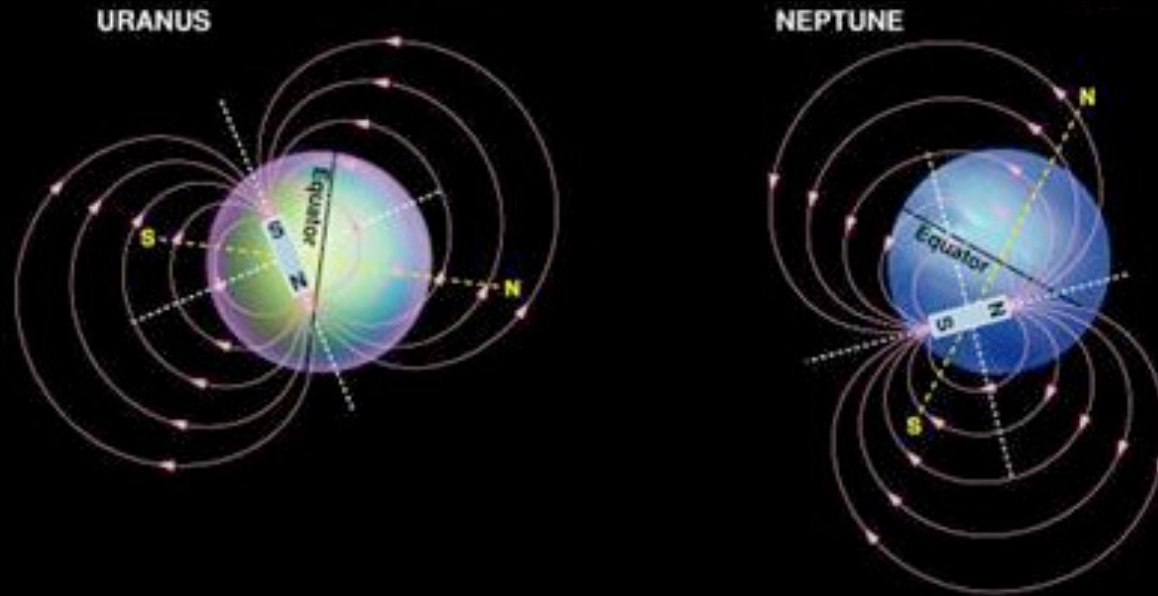


Neptune is also warmer than would be predicted just from the sunlight falling on it: the temperature of its outer atmosphere is 60 degrees Kelvin, whereas sunlight alone would produce 46 K. Heat must be flowing from its interior, as it does for Jupiter and Saturn. Uranus, however, does not have an internal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

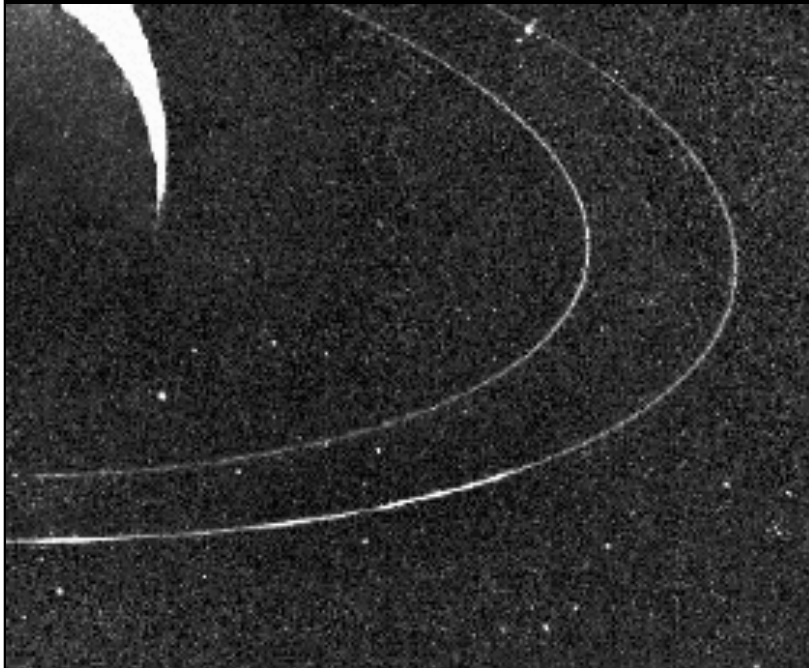
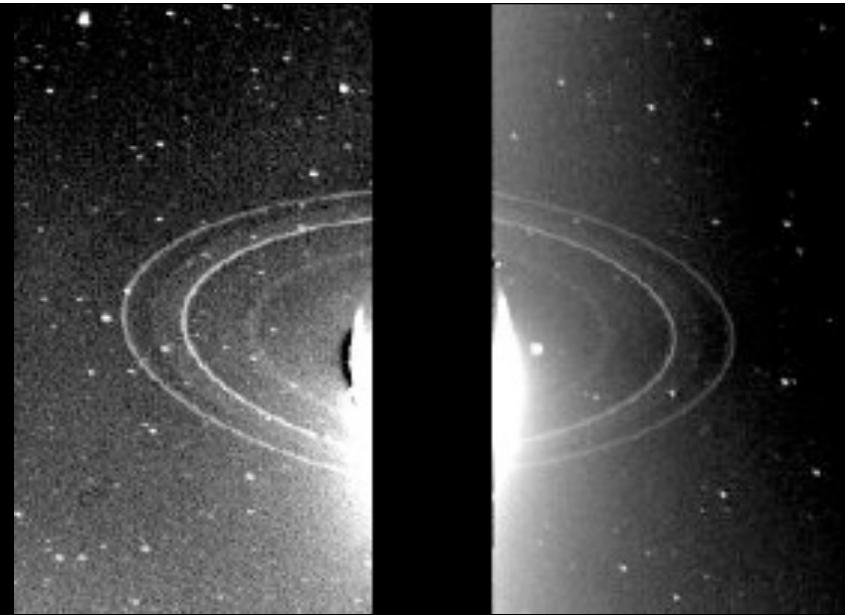
Like Uranus, Neptune might better be called an “ice giant” than a “gas giant” like Jupiter and Saturn, which contain 80-90% hydrogen and helium by mass. Uranus and Neptune contain between 5 and 20% hydrogen and helium. Like Uranus, underneath this atmosphere is a thick layer of water, methane and ammonia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



Like Uranus, Neptune's magnetic field is tilted (about 50°) and is displaced about halfway from the centre of the planet towards the edge. The field is much weaker than those of the other giant planets: about as strong as Earth's.

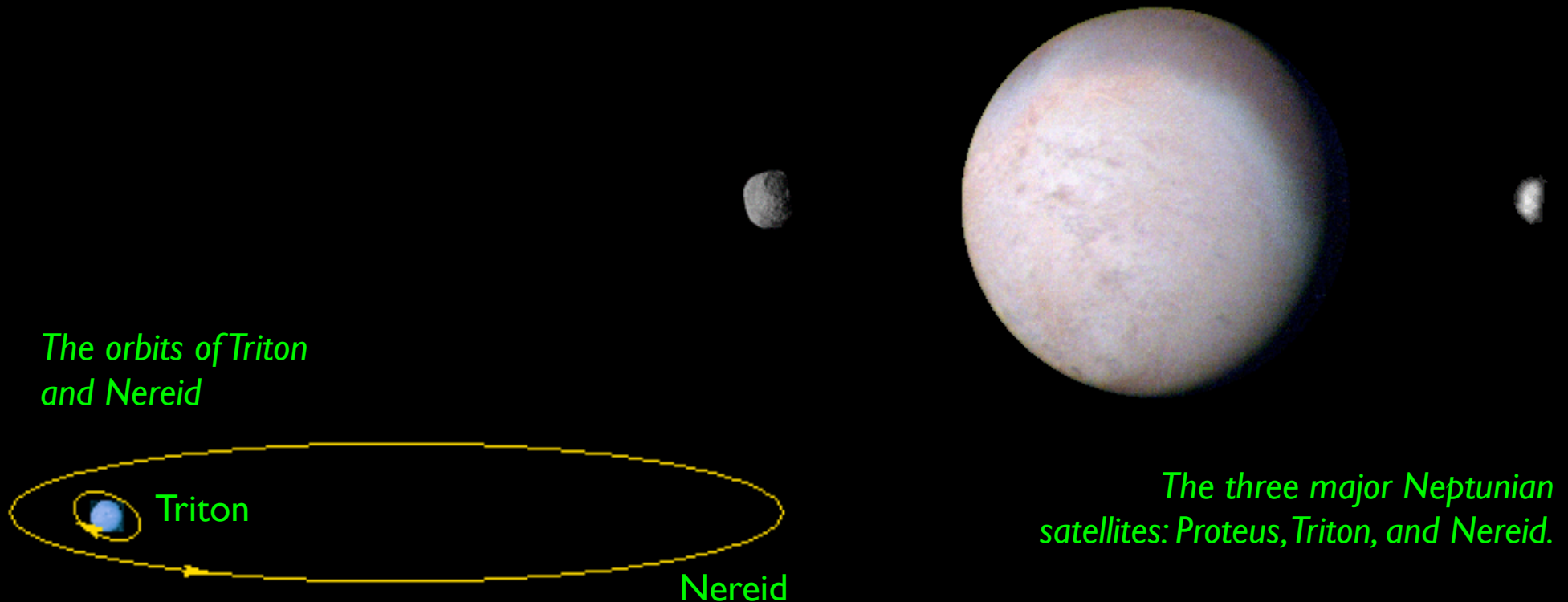


Neptune's rings are very faint and very dark. They contain large amounts of dust, and are probably rocky rather than icy.

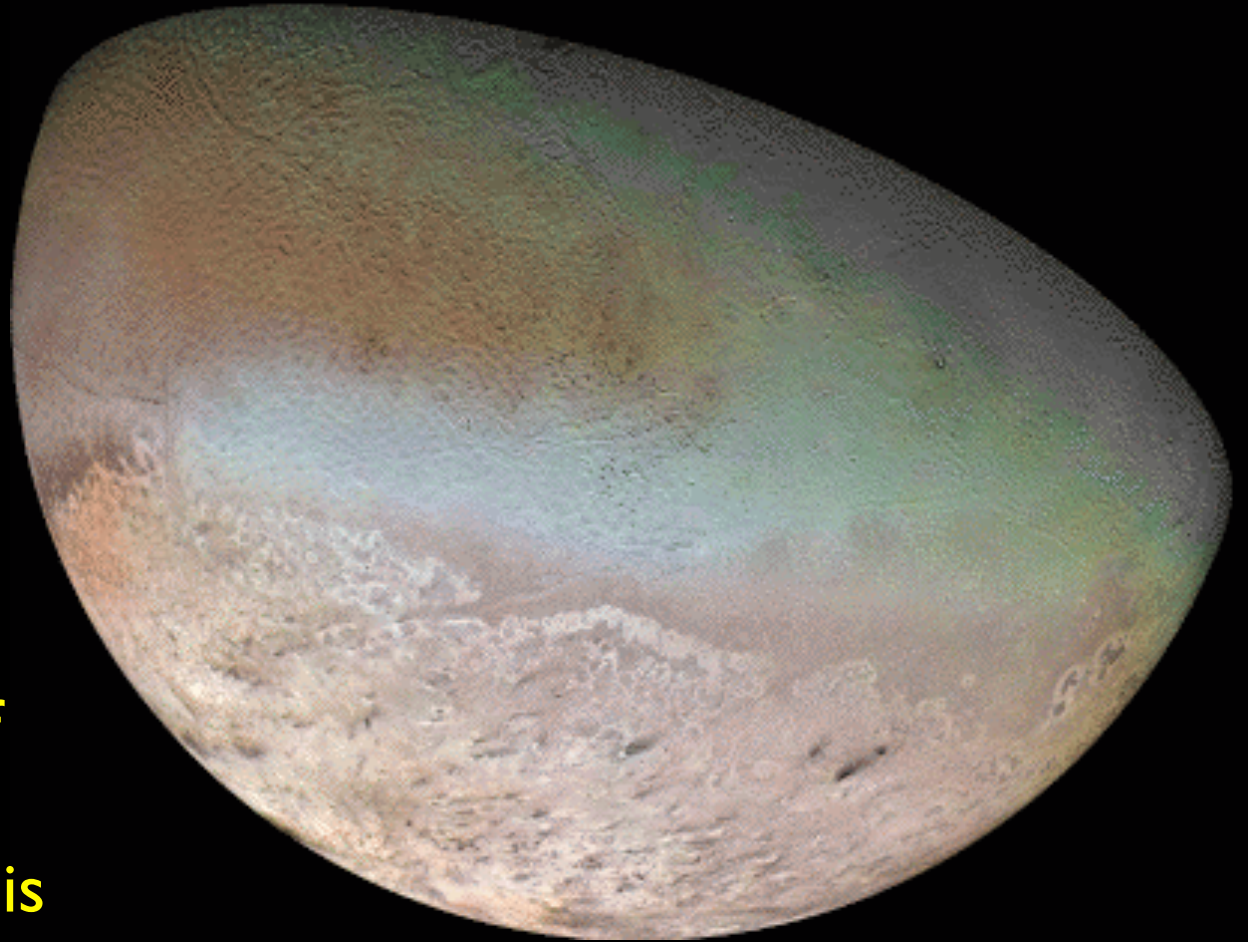


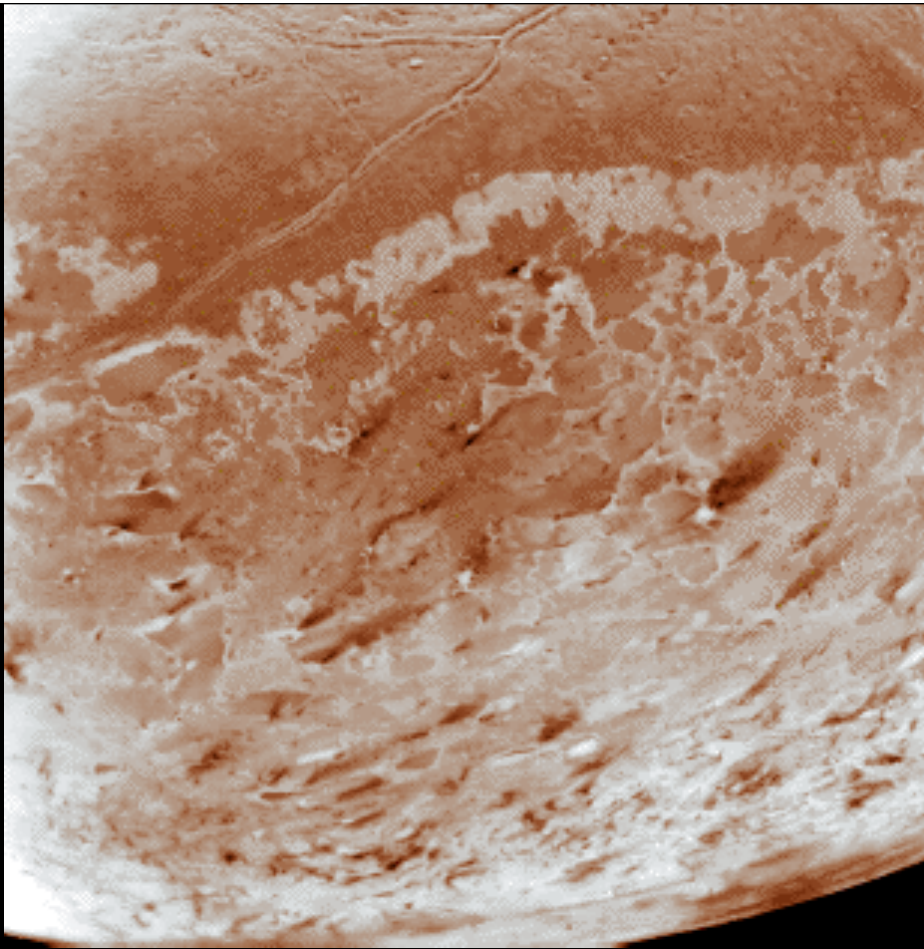
The rings are clumpy, with short arcs of denser material. These appear to be due to gravitational interaction with the small inner moon Galatea.

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.



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.

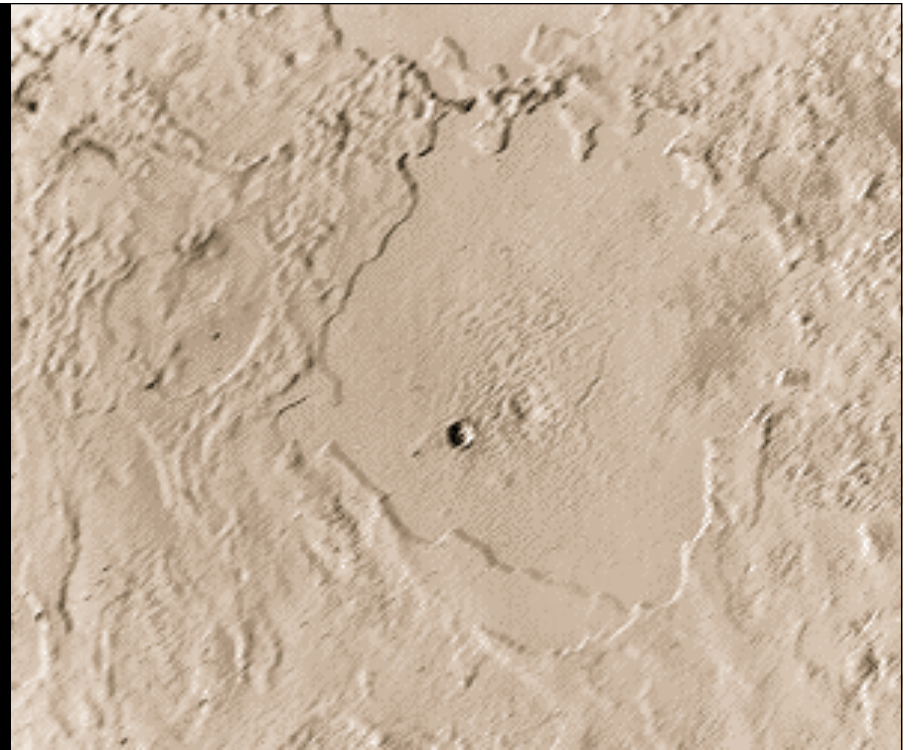




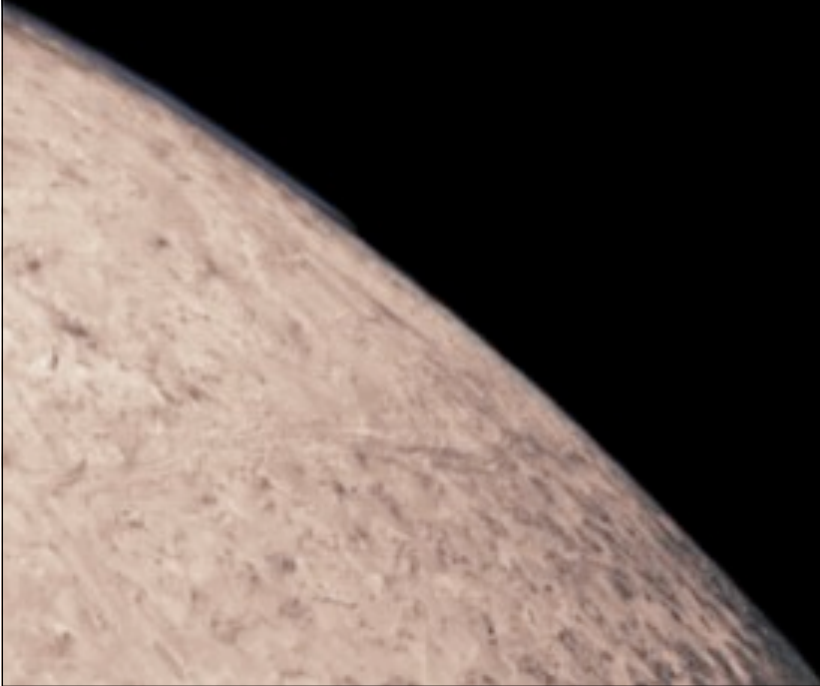
Voyager took this picture of Triton's south pole, revealing evidence of ice volcanoes. The dark streaks are material spread downwind from recent volcanic eruptions. The favoured mechanism for the volcanoes is that the Sun heats darkened methane ice on the surface, which heats underlying

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.



Of Neptune's other moons, six named moons were discovered by Voyager, and five more were recently discovered from the ground. The six Voyager moons are mostly closer to Neptune than the rings, and are considered regular, since they orbit in the equatorial plane in the same direction as Neptune.

Five new moons were discovered in 2002–3, all small (< 40 km), very distant from Neptune, and in highly eccentric and inclined orbits.

Artist's impression of three new moons of Neptune.



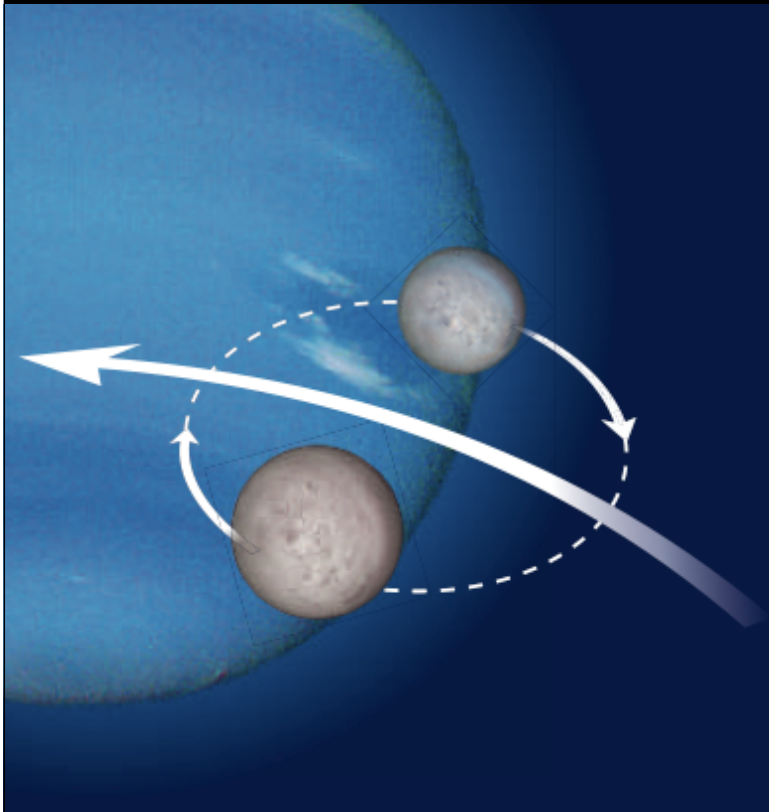
It is likely that Triton formed in the Kuiper belt and was captured when it ventured too close to Neptune. One suggestion is that Neptune originally had its own more normal family of moons. Triton collided with a small icy moon, with a mass a few percent of Triton's. The collision completely destroyed 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.

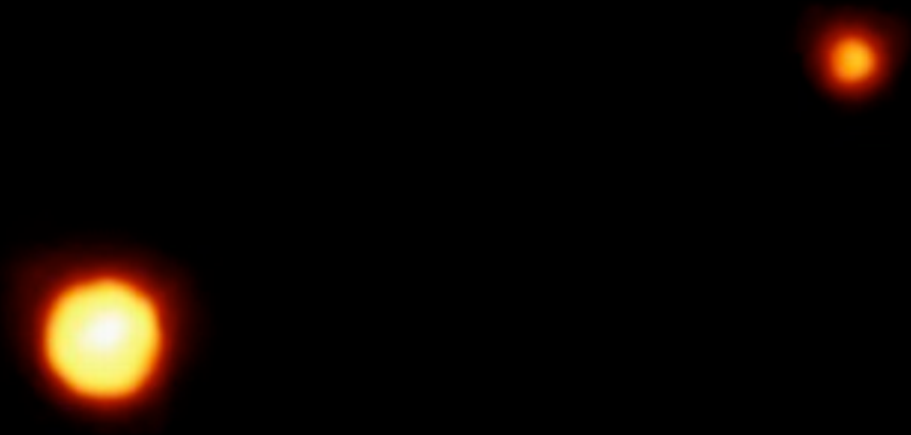


During the interaction, as the binary was ripped apart, one object was moving more slowly relative to Neptune and so could be captured into a bound orbit relatively gently.

Pluto & Charon

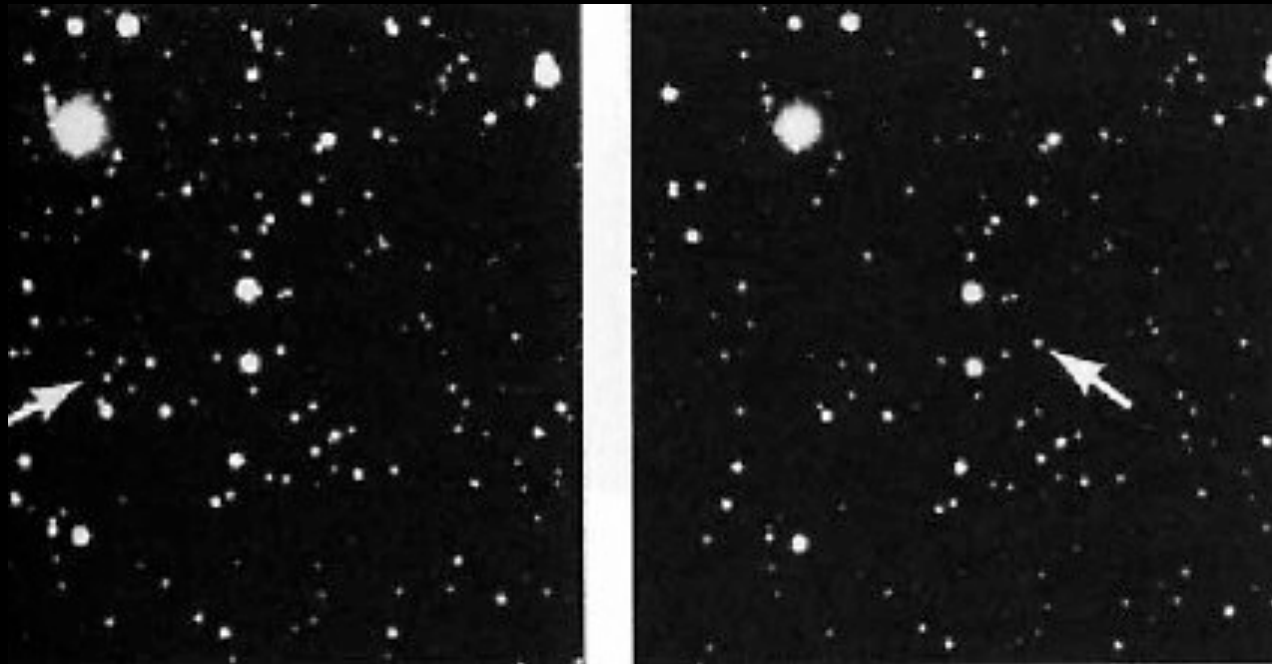


Pluto and Charon form an enigmatic double at the outer edge of the Solar System. They orbit each other once a week, in a highly eccentric orbit around the Sun which is tilted well out of the plane of the ecliptic. The combined mass of Pluto and Charon is less than one percent of Earth's. Pluto is now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



*HST image of Pluto and Charon
taken in 1994*

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.

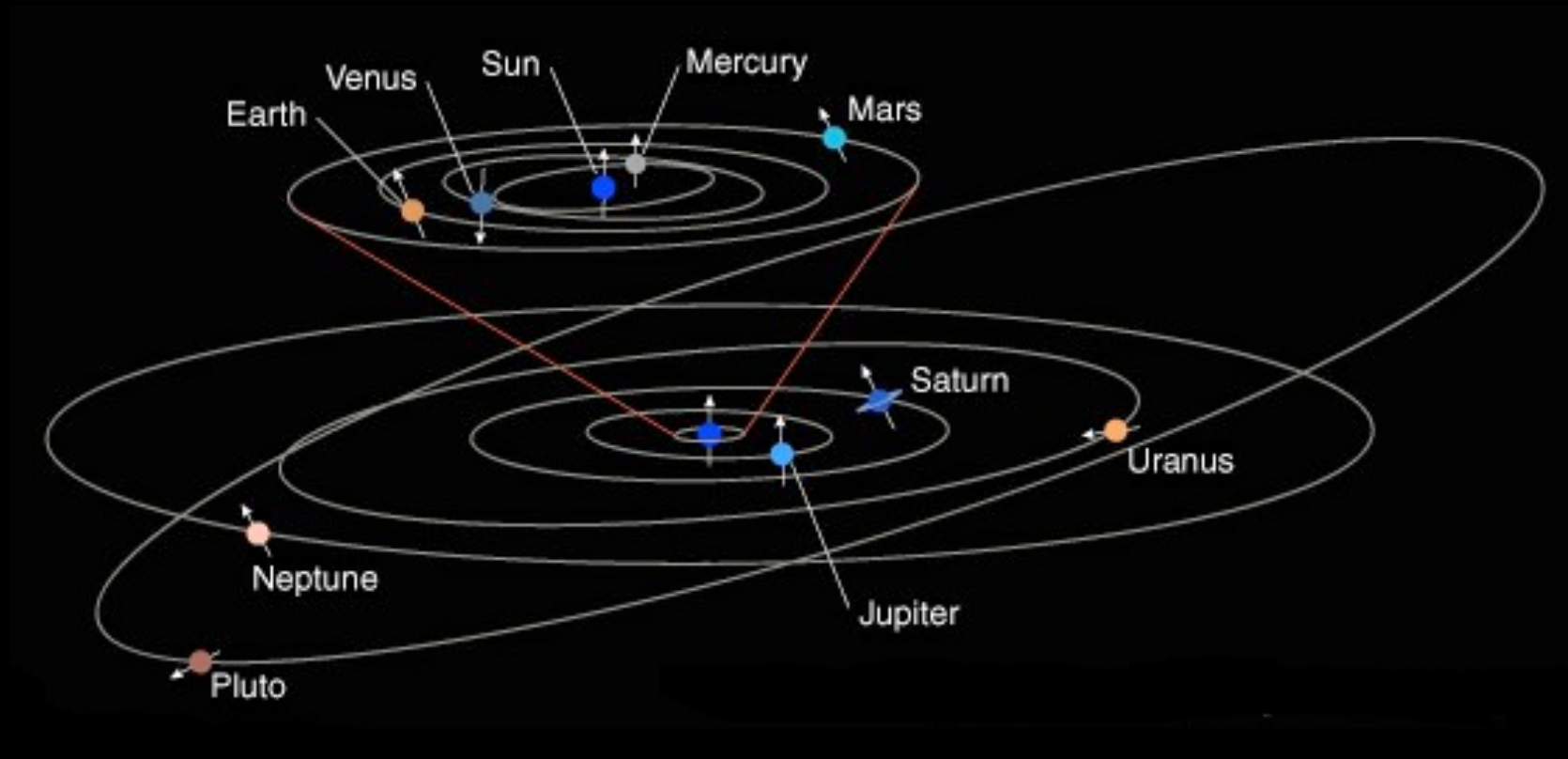


The discovery images for Pluto, showing the star moving between the two exposures, taken two weeks apart.

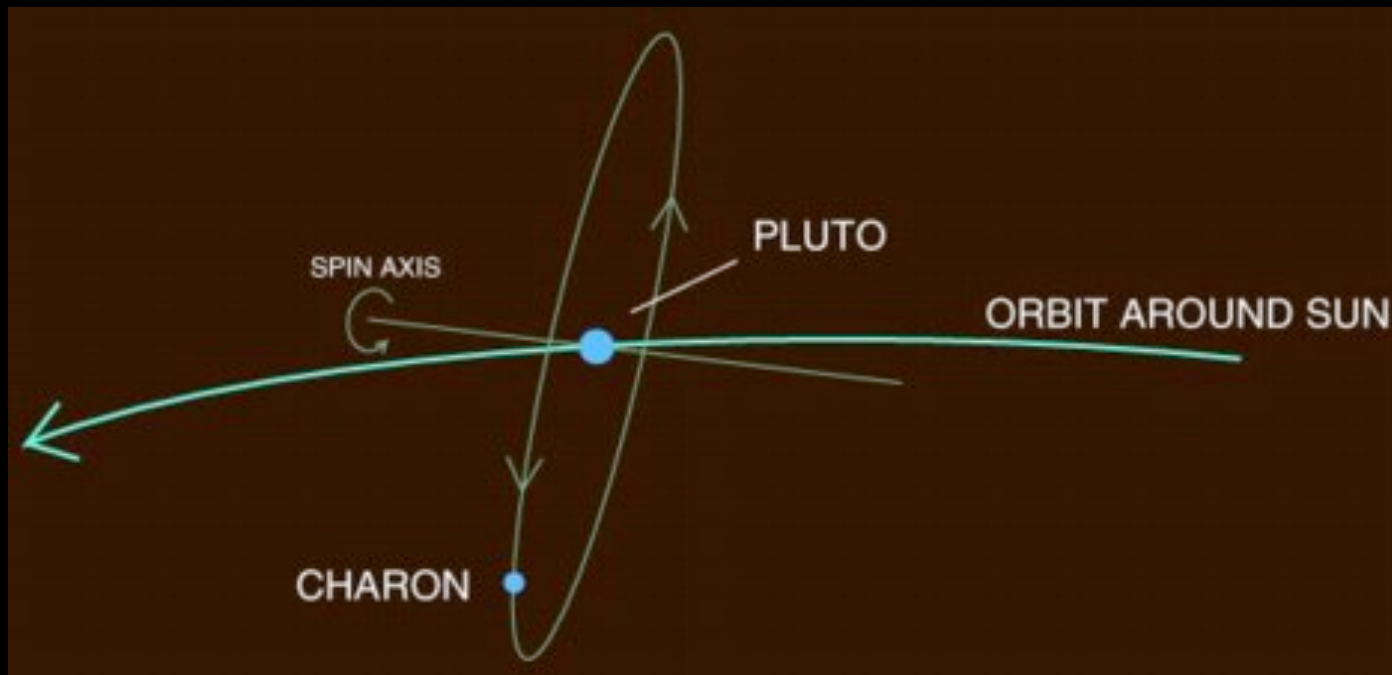
Basic facts

	Pluto/Charon		Pluto/Charon / Earth	
Mass	$0.0125 \times 10^{24} \text{ kg}$	$0.0019 \times 10^{24} \text{ kg}$	0.0021	0.00032
Radius	1195 km	593 km	0.187	0.093
Mean density	1.75 g/cm^3	1.85 g/cm^3	0.317	0.335
Semi-major axis	$5870 \times 10^6 \text{ km}$		39.236	
Period	90 465 d		247.68	
Orbital inclination	17.16°		-	
Orbital eccentricity	0.2444		14.6	
Tilt of axis	122.53°		5.3	
Surface gravity	0.58 m/s^2		0.059	
Rotation period	-153.2928 h		6.405	
Length of day	153.2820 h		6.387	

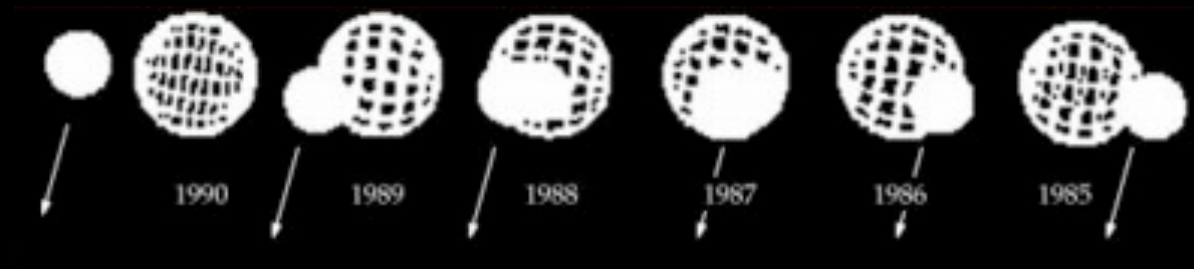
Pluto's highly elongated orbit takes it from 29.7 AU (within the orbit of Neptune) to 49.3 AU. It crossed back outside Neptune's orbit in March 1999. Pluto's orbit is also inclined by 17° to the plane of the ecliptic. Pluto is locked in a 3:2 resonance with Neptune, so its orbital period is exactly 1.5 times longer than Neptune's.



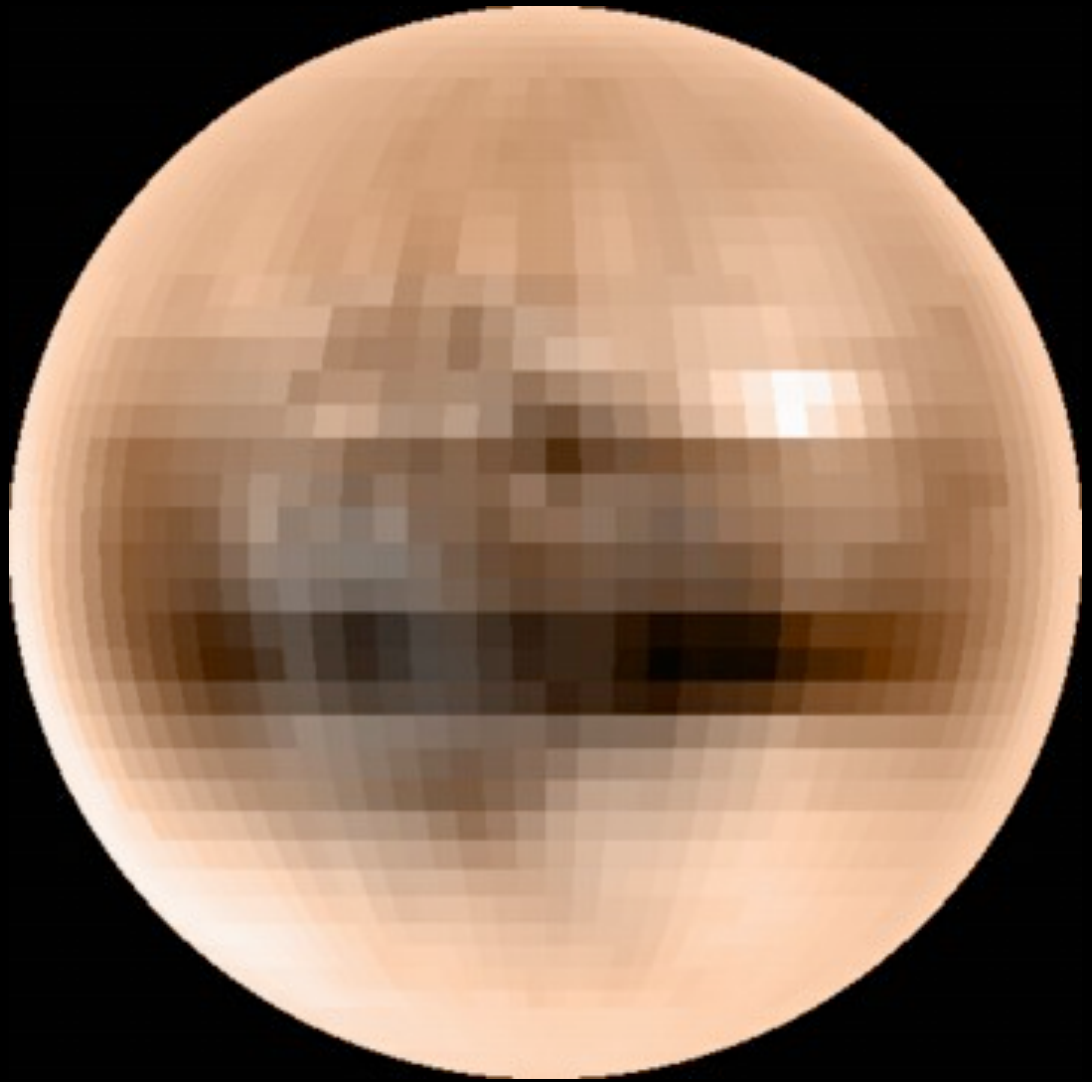
In 1978, Pluto was found to have a satellite with an orbital period of 6.4 days, which was named Charon. Like Neptune, Pluto orbits on its side, and Charon orbits in its equatorial plane. By good fortune, Charon was discovered just before its orbital plane became edge-on to us, so from 1985 to 1990 Charon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



It was therefore possible to observe many transits of Pluto over Charon and vice versa. By keeping track of what part of Pluto was covered up and how dim the combined image of the planet and its moon became, astronomers could tell how bright the covered-up parts of Pluto must be. After watching many eclipses, they could piece together a mosaic of Pluto's surface (at least the half of Pluto that always faces Charon). By recording eclipses in several colours, they could even make a colour map of Pluto.

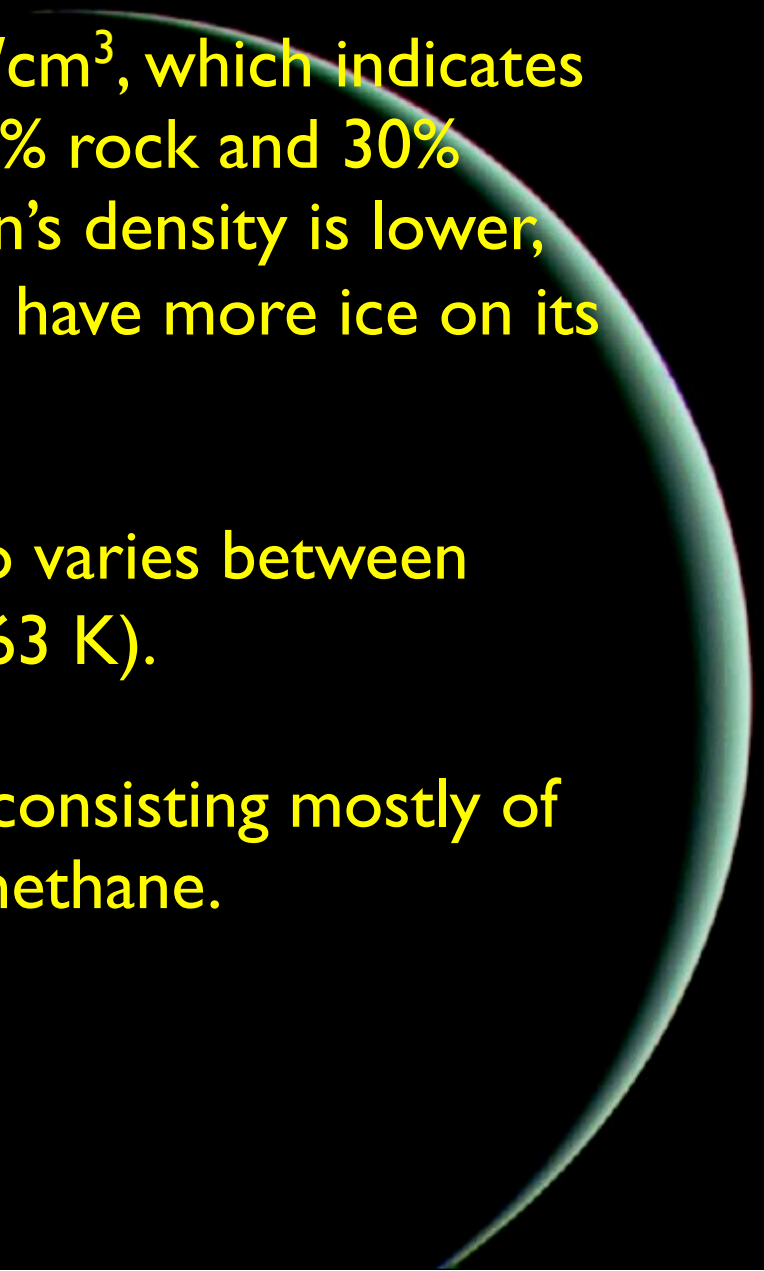


This map of Pluto was made from over 22 eclipse observations from 1985 to 1990. The brighter areas are mainly nitrogen frost. Most of Pluto has a red-brown tint, which is probably frozen methane deposits metamorphosed by faint but energetic sunlight (think condensed smog!).



HST can resolve Pluto (barely), well enough to 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). Topographic features such as basins, or fresh impact craters may cause some of the variations across Pluto's surface.



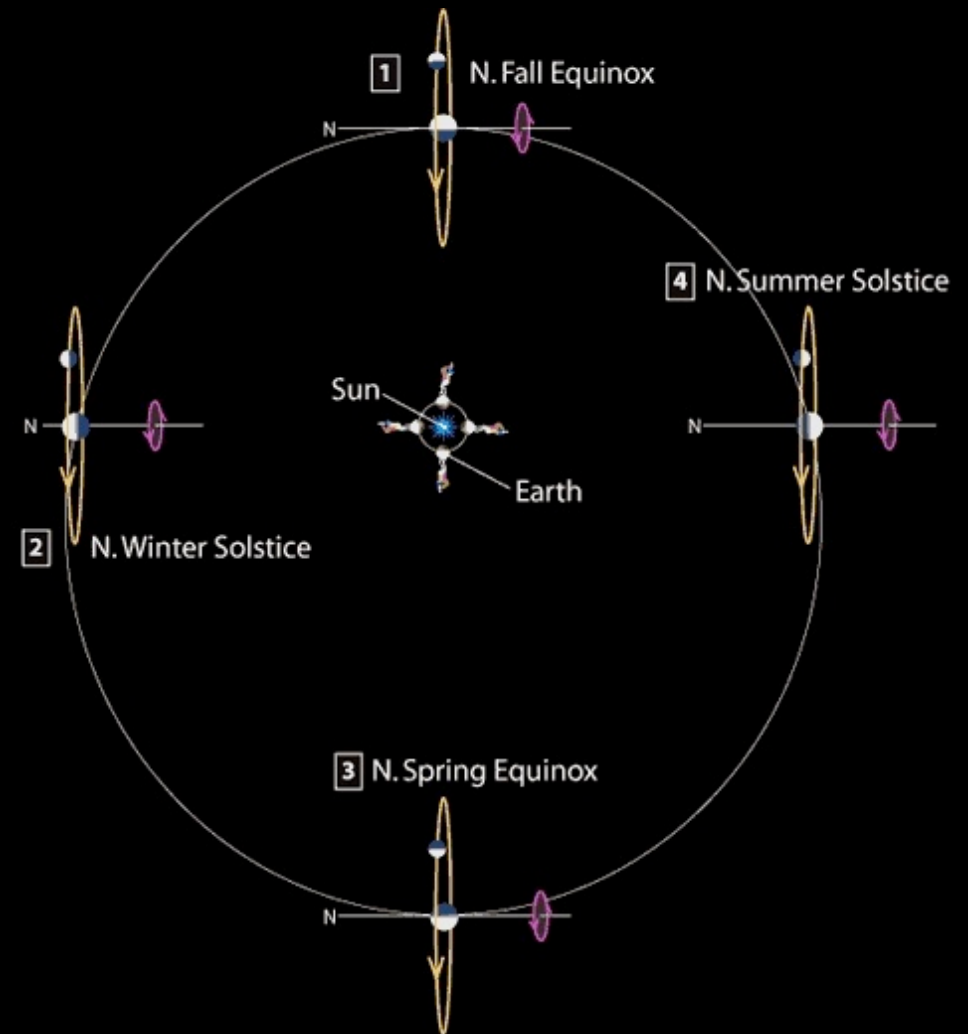


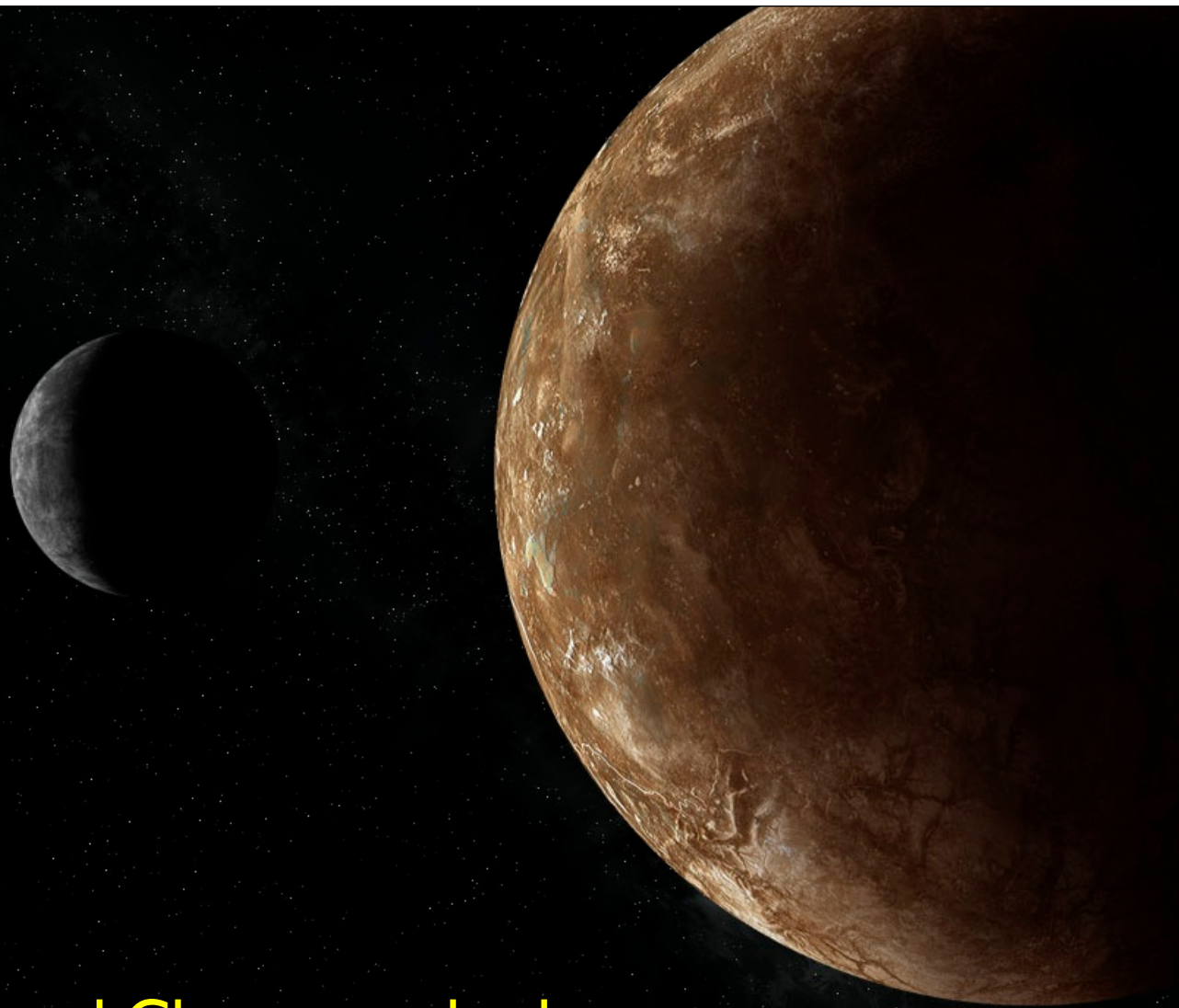
Pluto has a low density, about 2 g/cm^3 , which indicates that it is probably a mixture of 70% rock and 30% water ice much like Triton. Charon's density is lower, about 1.3 g/cm^3 , and it appears to have more ice on its surface.

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.

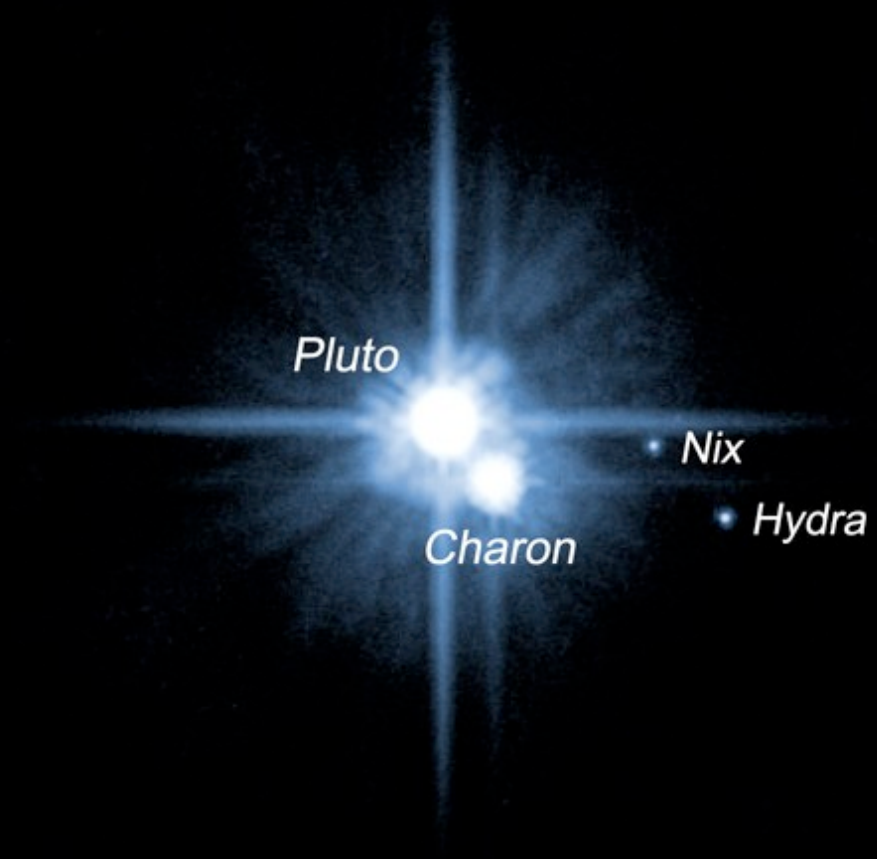
Like Uranus, Pluto has extreme seasons because of its orbital tilt. Pluto's south pole is just entering its arctic night after half a Pluto year (124 Earth years!) of constant illumination.





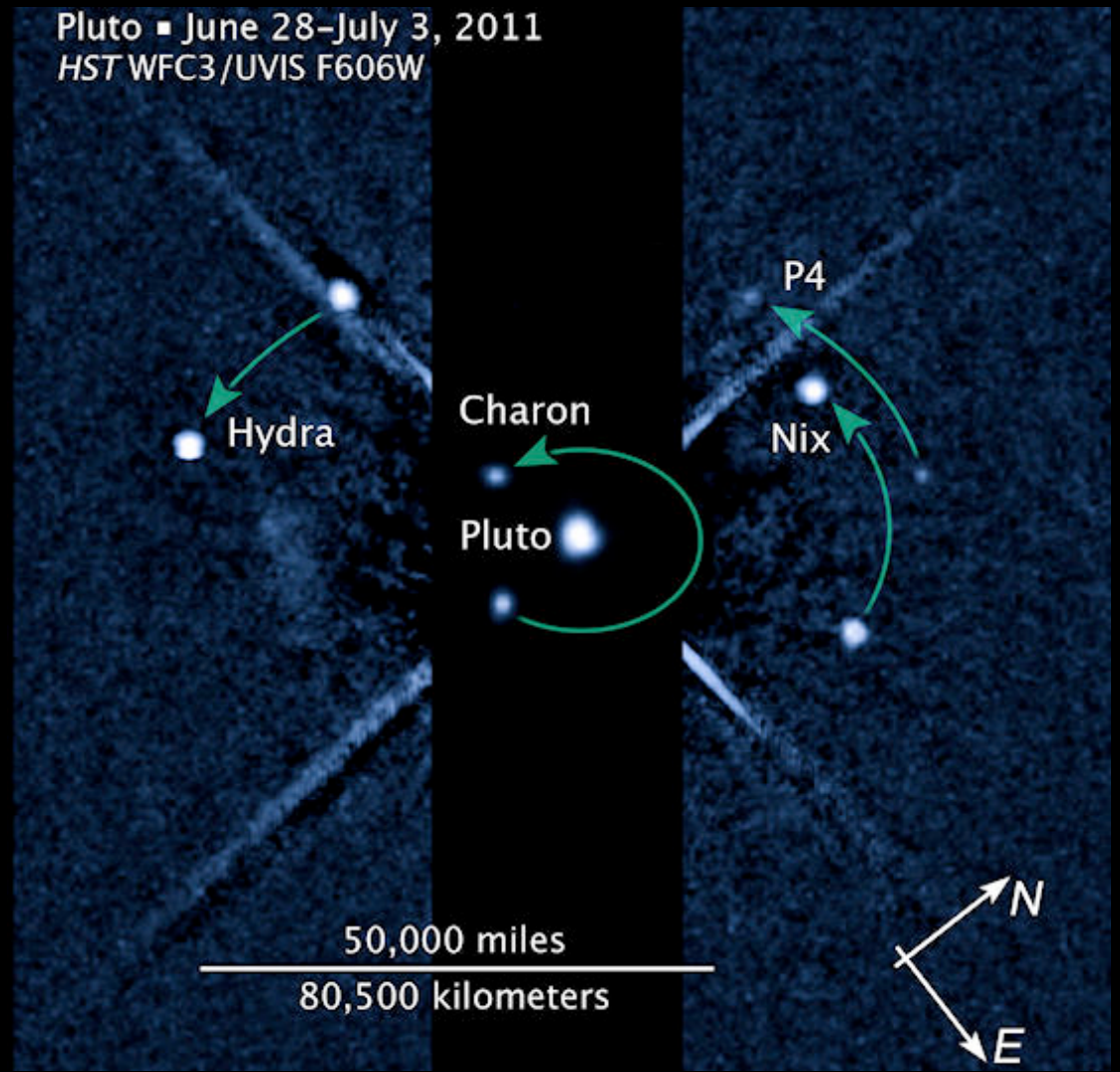
Pluto and Charon are both tidally locked, so they always present the same face to each other. From one side of Pluto, Charon would stay in the same place in the sky as the stars rotated past, while from the far side you would never see Charon at all.

In 2005 two small moons were discovered: *Nix* and *Hydra*. They orbit at approximately two and three times the distance of Charon; their sizes are not yet known, but they are probably 40–60 km in size. Even if they were as dark as the darkest Kuiper belt objects, they couldn't be bigger than about 170 km.

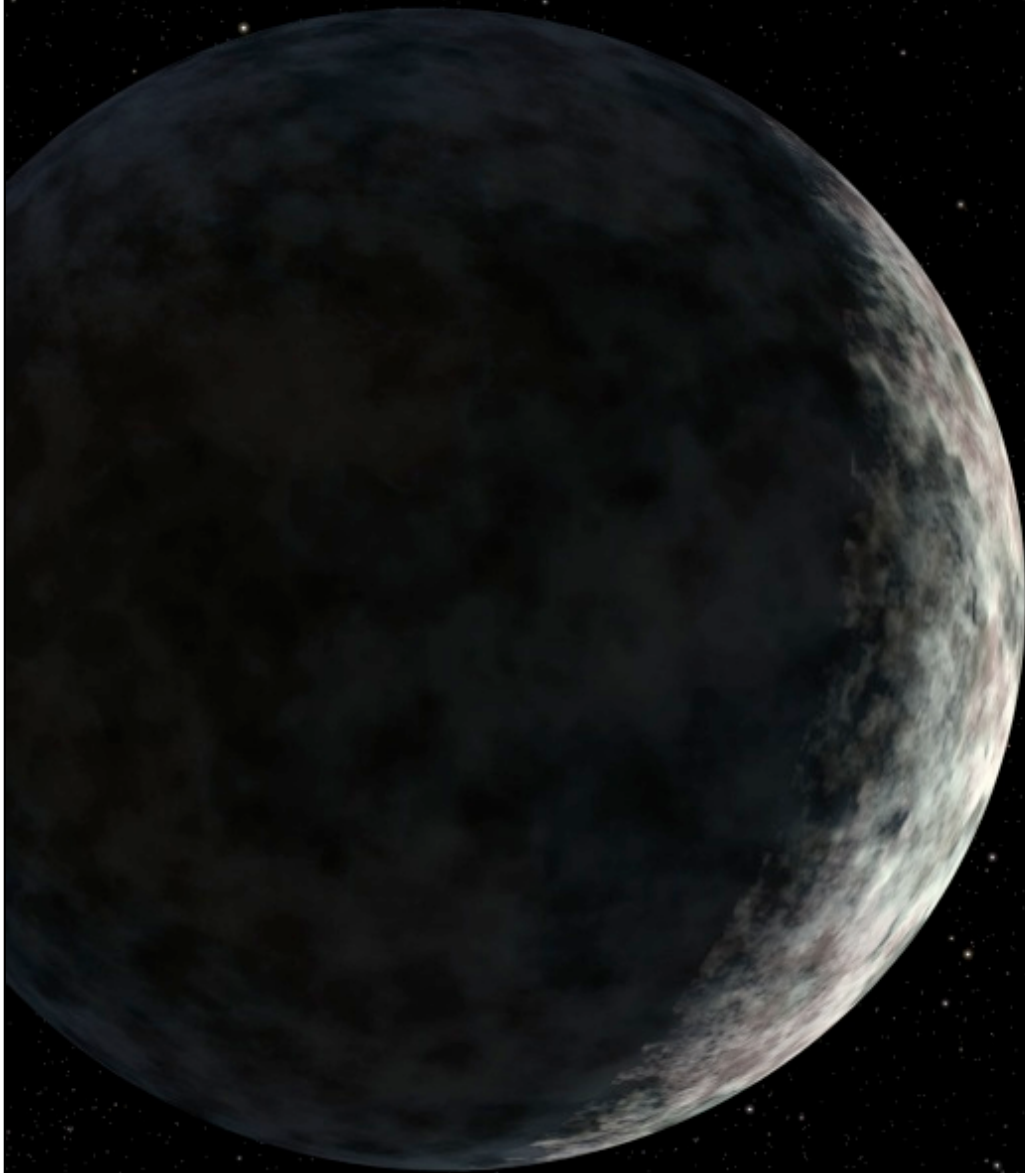


Hubble image of Pluto and its moons

In July this year, Hubble discovered a *fourth* moon of Pluto (as yet unnamed). It orbits between Nix and Hydra.

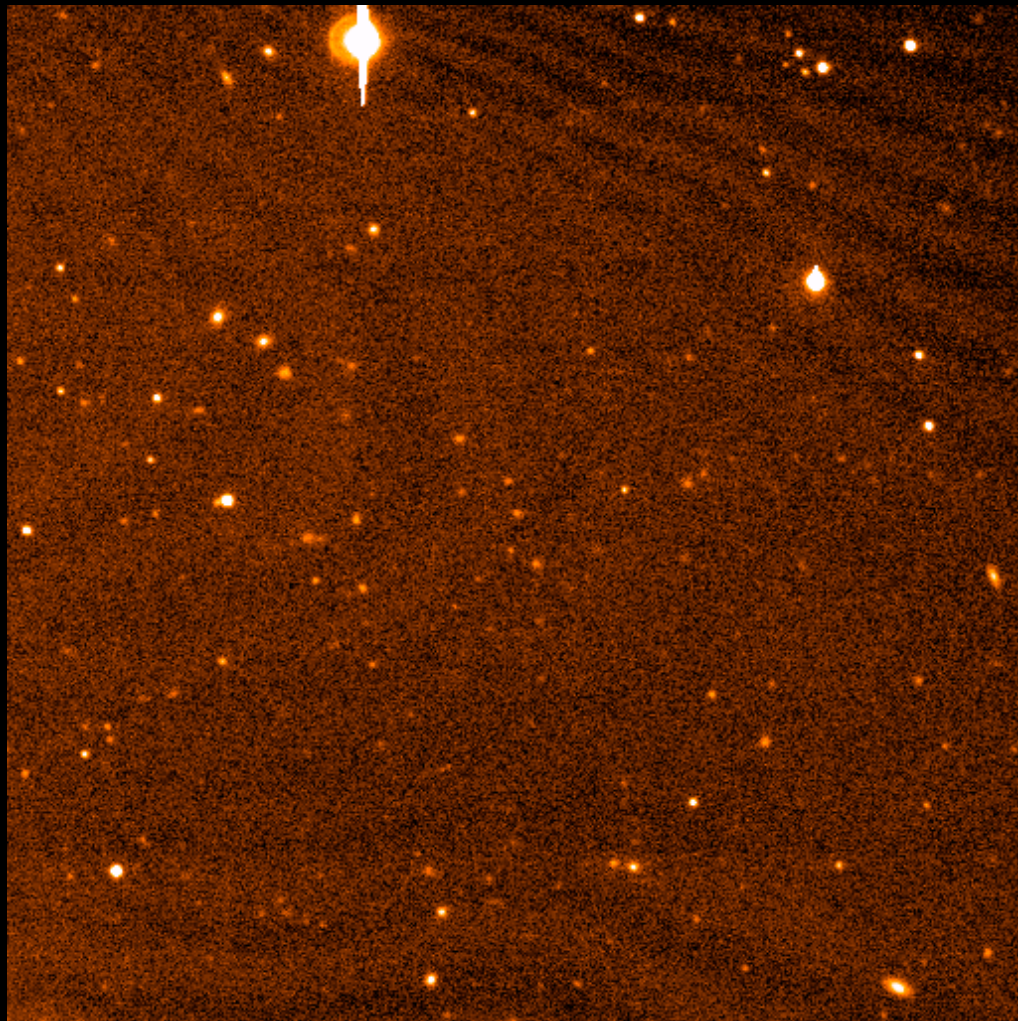


Eris

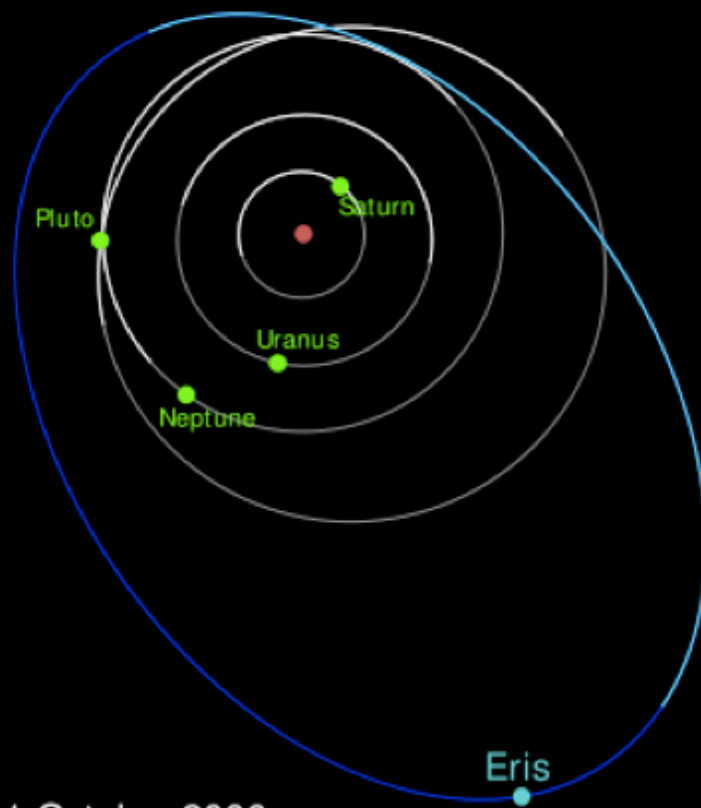


In 2005, three astronomers searching for Kuiper belt objects found a new object, even larger than Pluto. It was given the temporary designation 2003 UB313, and later called Eris. Its orbit is even more eccentric than that of

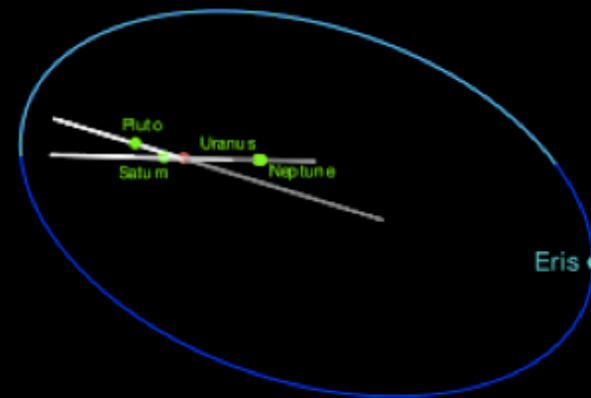
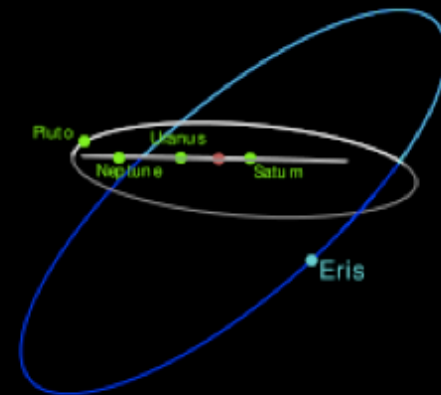
Pluto. Pluto's distance from the Sun varies between 30 and 50 AU over its 250 year orbit, while Eris moves from 38 to 97 AU over its 560 year orbit.



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



11 October 2006



Orbit of Eris (136199 Eris)

Perihelion: 37.77 AU

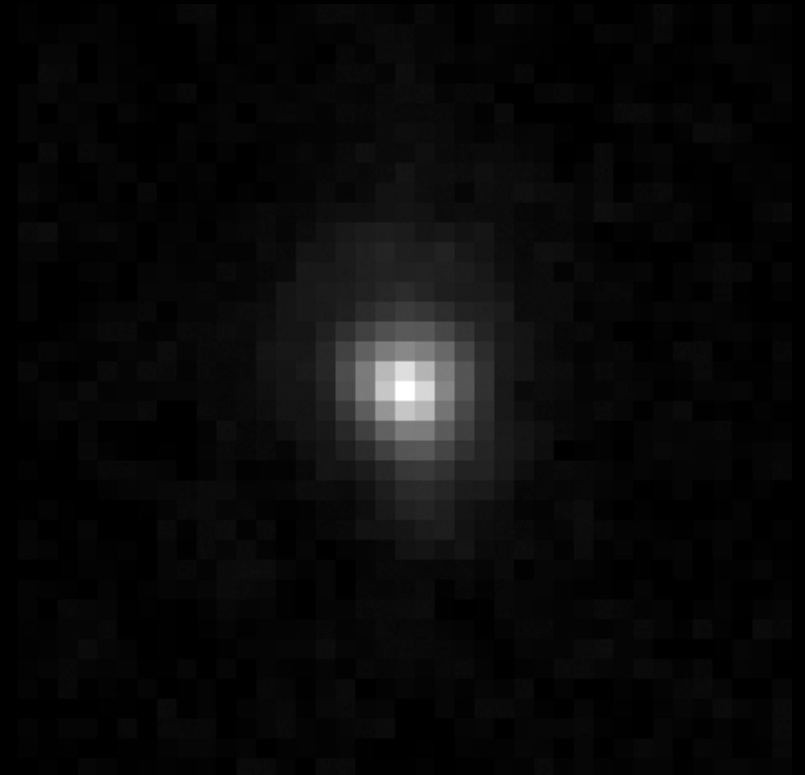
Aphelion: 97.56 AU

Orbital period: 557 years

Eccentricity: 0.44

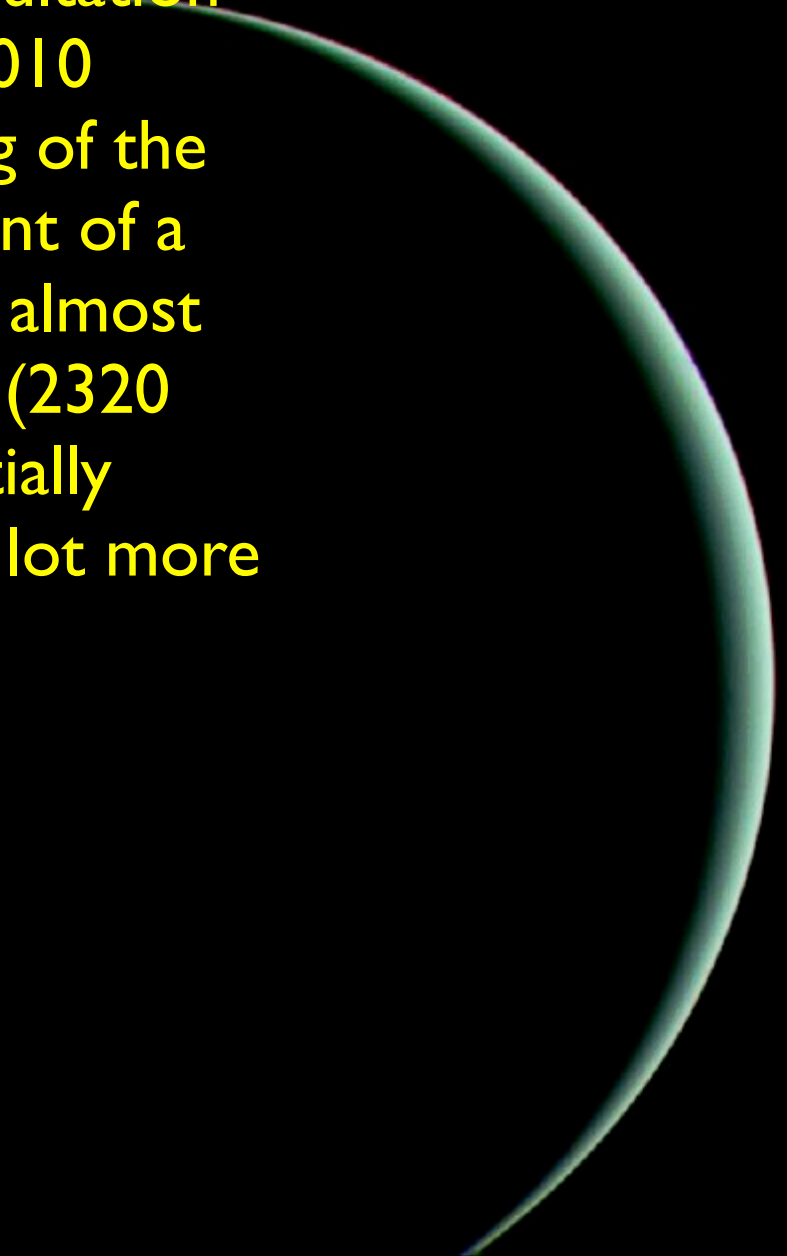
Inclination: 44°

Eris' diameter was measured using the Hubble Space Telescope to be 2400 ± 100 km, making it (just!) the largest dwarf planet in the solar system. 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. Recent Spitzer measurements suggest its size might be somewhat larger, up to 30% larger than Pluto.

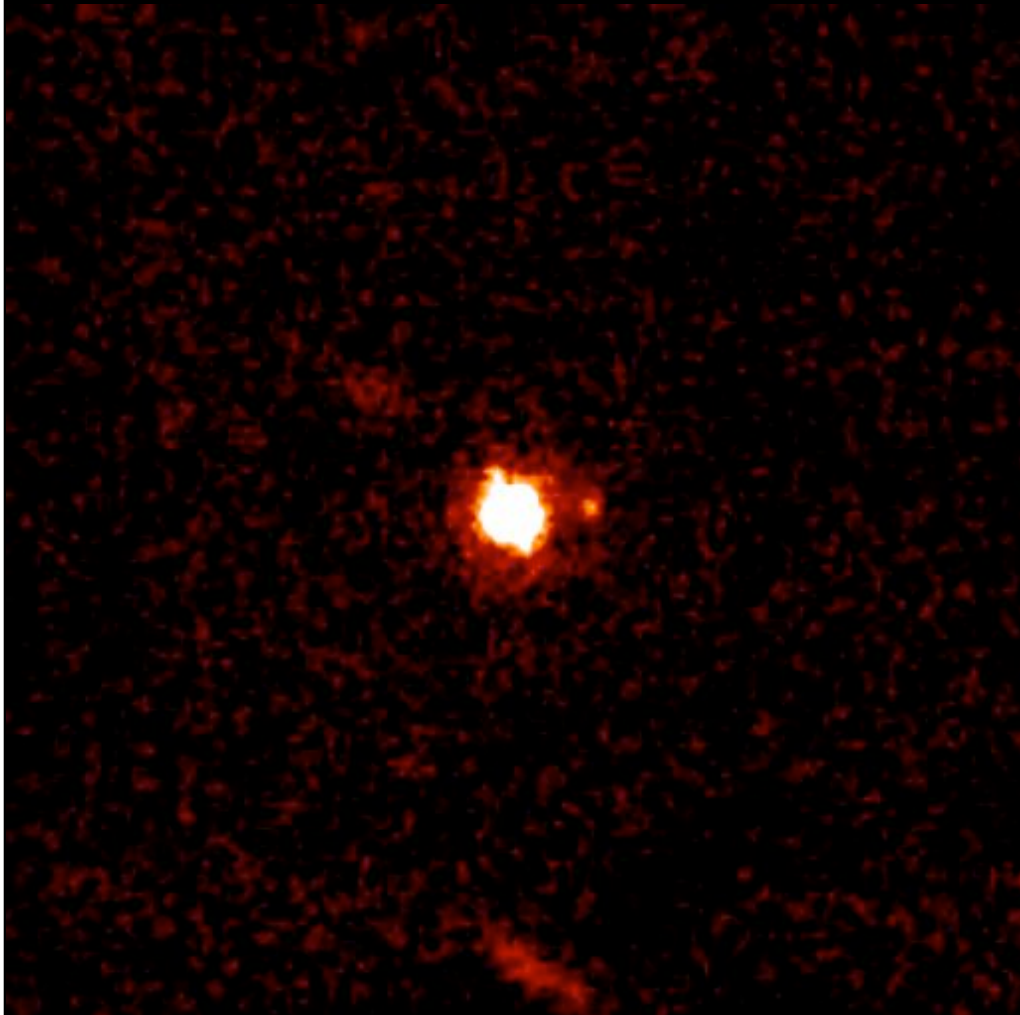


The best image of Eris, taken by Hubble.

And in yet another twist, an occultation of a star by Eris in November 2010 reduced its size again. The timing of the occultation, as Eris drifted in front of a background star, reveal that it is almost precisely the same size as Pluto (2320 km), indicating that it is substantially denser. This must mean it has a lot more rock than Pluto – but why?



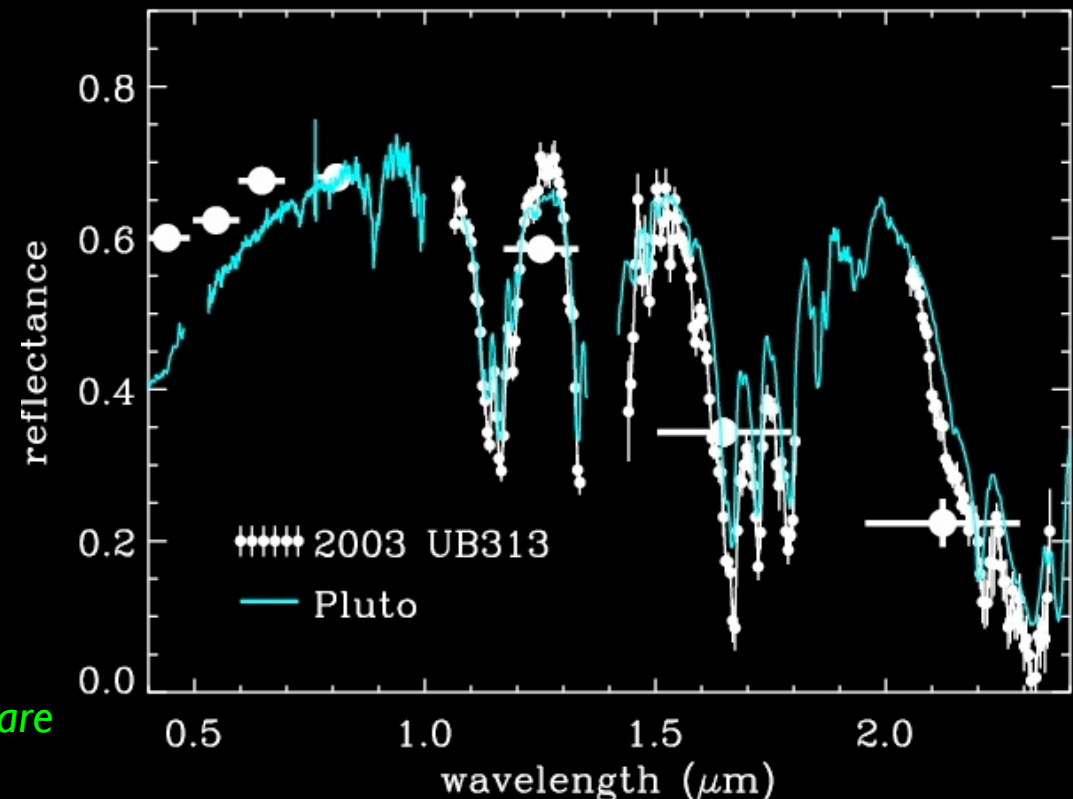
In 2006, after the decision regarding the definition of a planet, the new body was given the name *Eris*, the Greek goddess of warfare and strife. Eris' satellite is called *Dysnomia*, Eris' daughter and the demon spirit of lawlessness.



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)

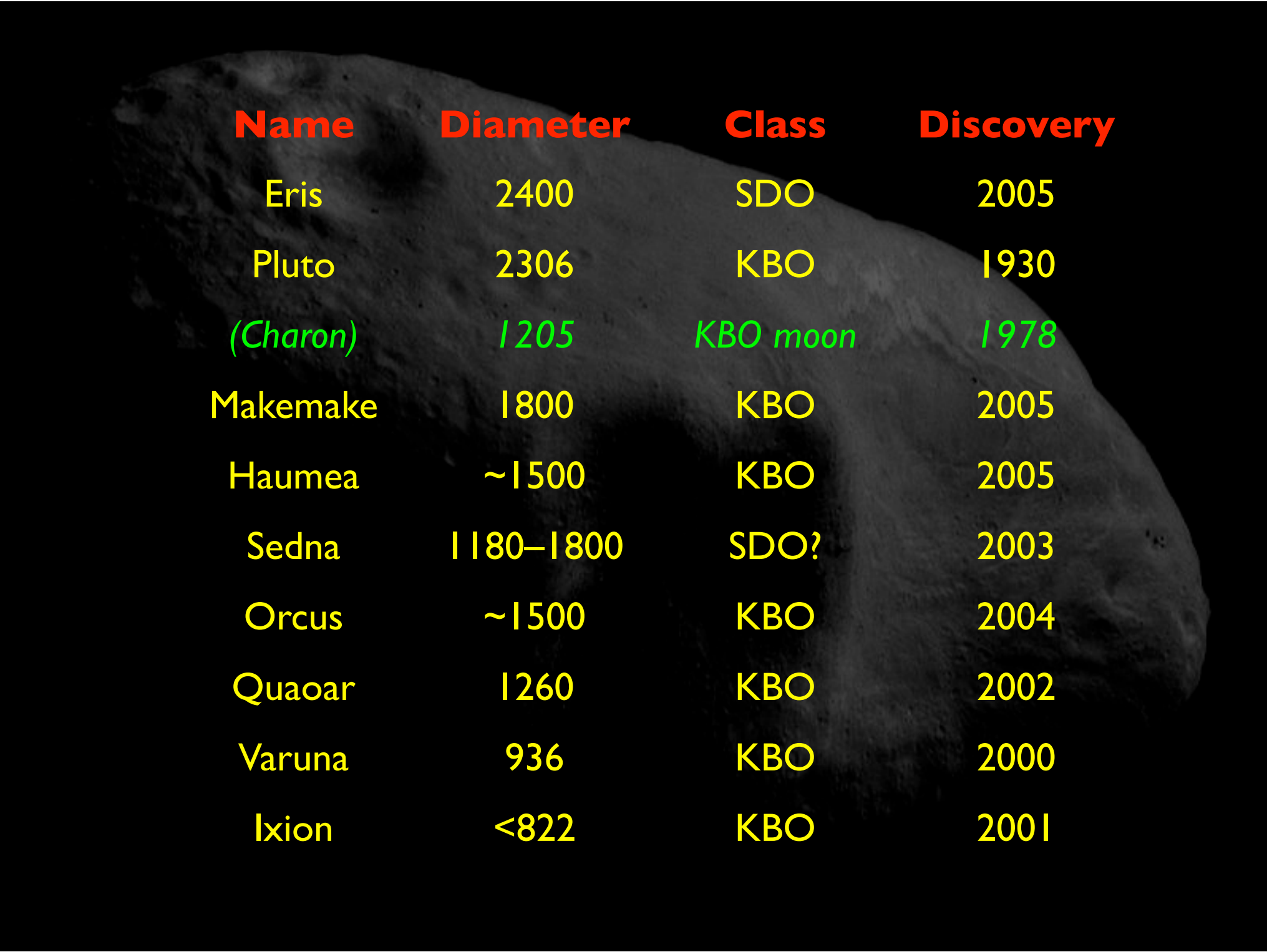
The best suggestion for this brightness is that, since the planet is now at aphelion and as far away from the Sun as it gets, its atmosphere has frozen completely, leaving the planet with a bright covering of several inches of frozen methane and nitrogen. Over the next 280 years, the surface will warm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



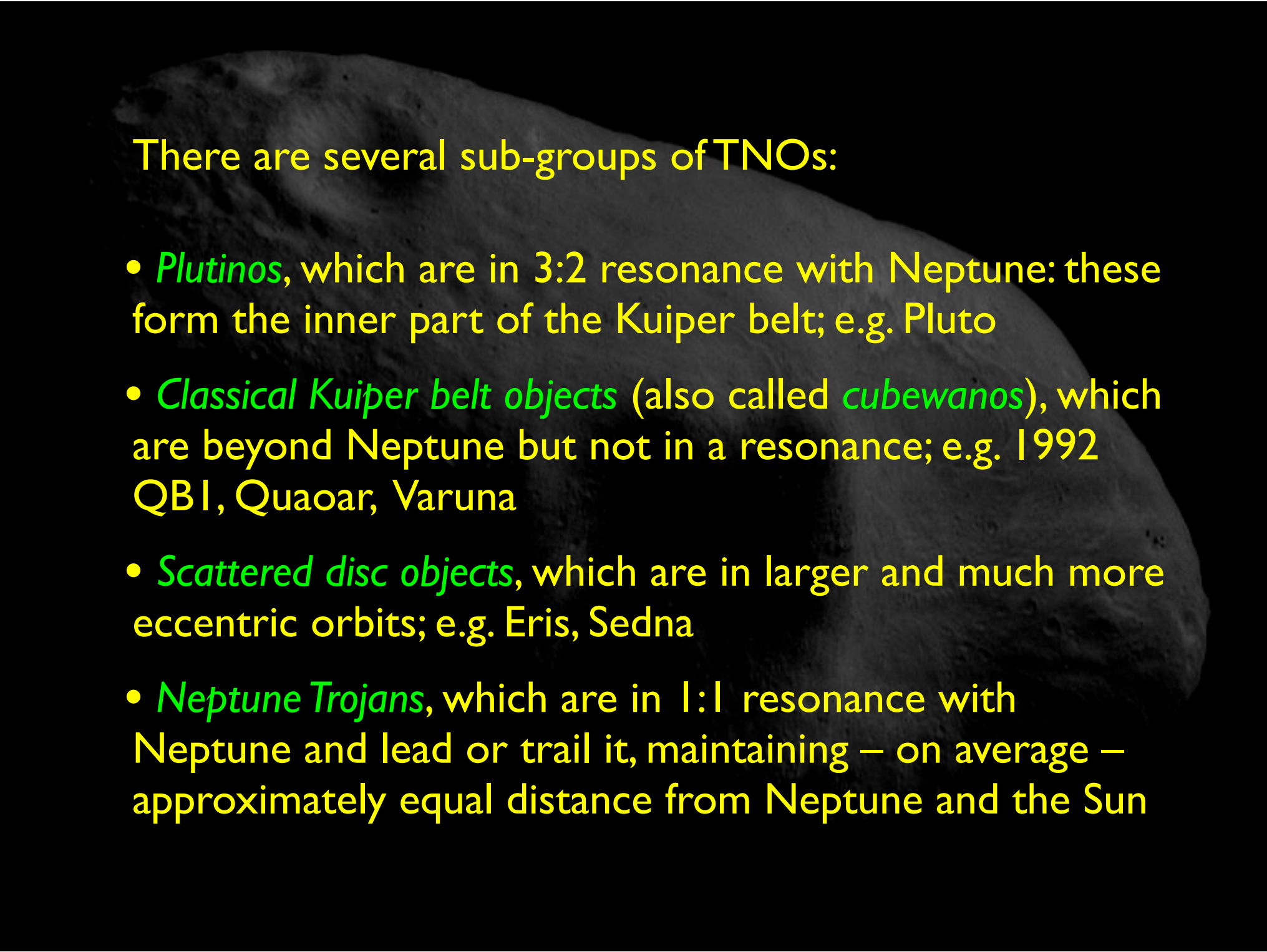
Infrared reflectance of Eris and Pluto. The dips are all due to solid frozen methane.

Eri and Pluto are the largest of the *trans-Neptunian objects* (TNOs). As of 2011, there were more than 1200 objects known beyond the orbit of Neptune. At least eight TNOs (plus Charon) have diameters of more than 1000 km.



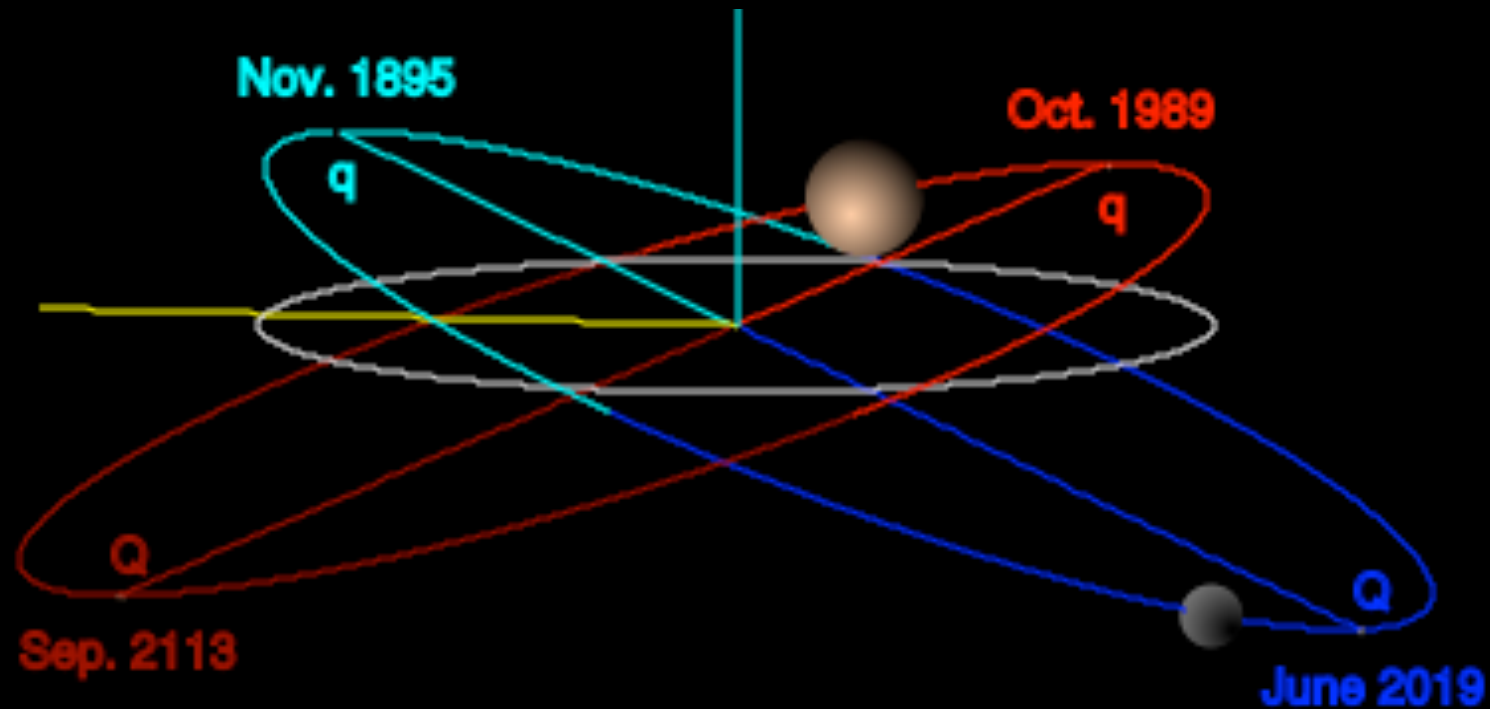


Name	Diameter	Class	Discovery
Eris	2400	SDO	2005
Pluto	2306	KBO	1930
(Charon)	1205	KBO moon	1978
Makemake	1800	KBO	2005
Haumea	~1500	KBO	2005
Sedna	1180–1800	SDO?	2003
Orcus	~1500	KBO	2004
Quaoar	1260	KBO	2002
Varuna	936	KBO	2000
Ixion	<822	KBO	2001

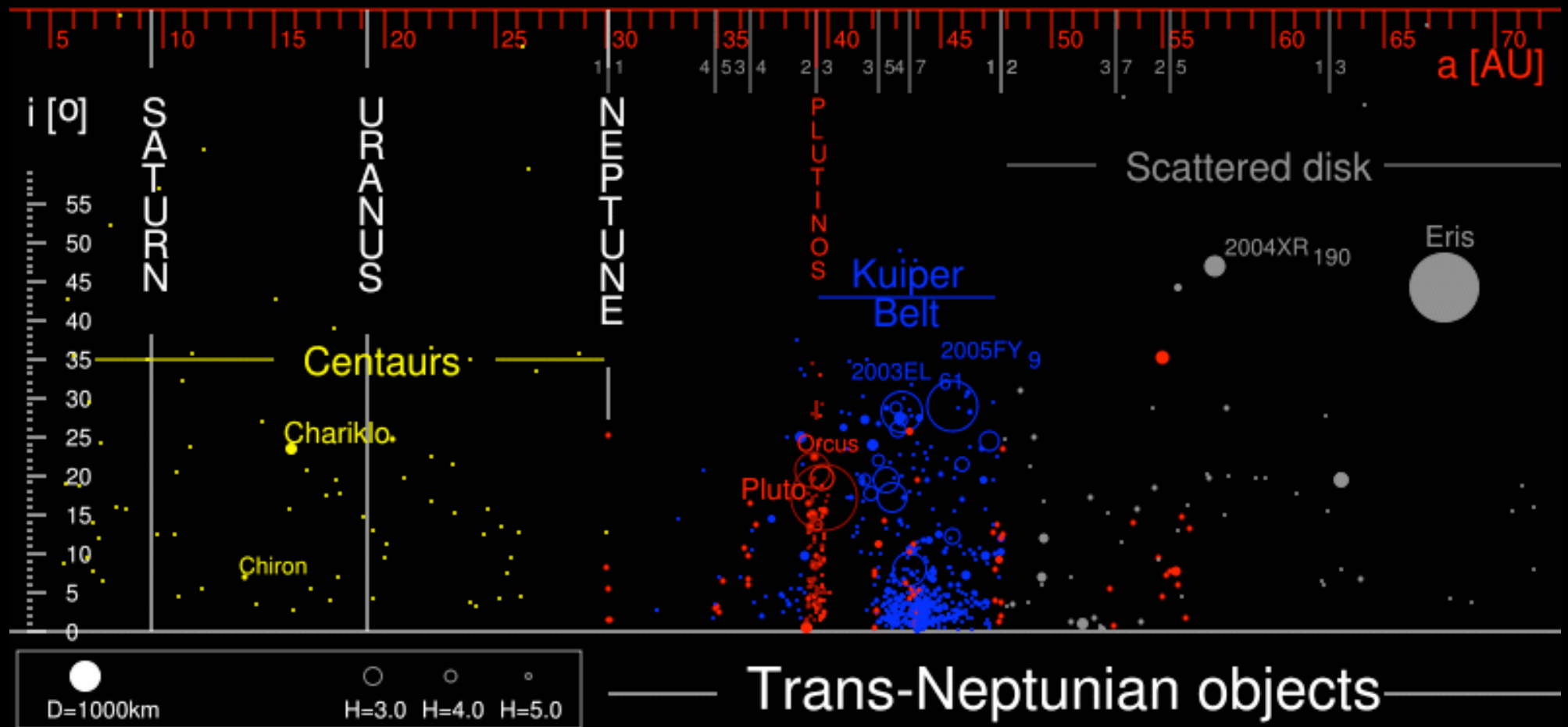


There are several sub-groups of TNOs:

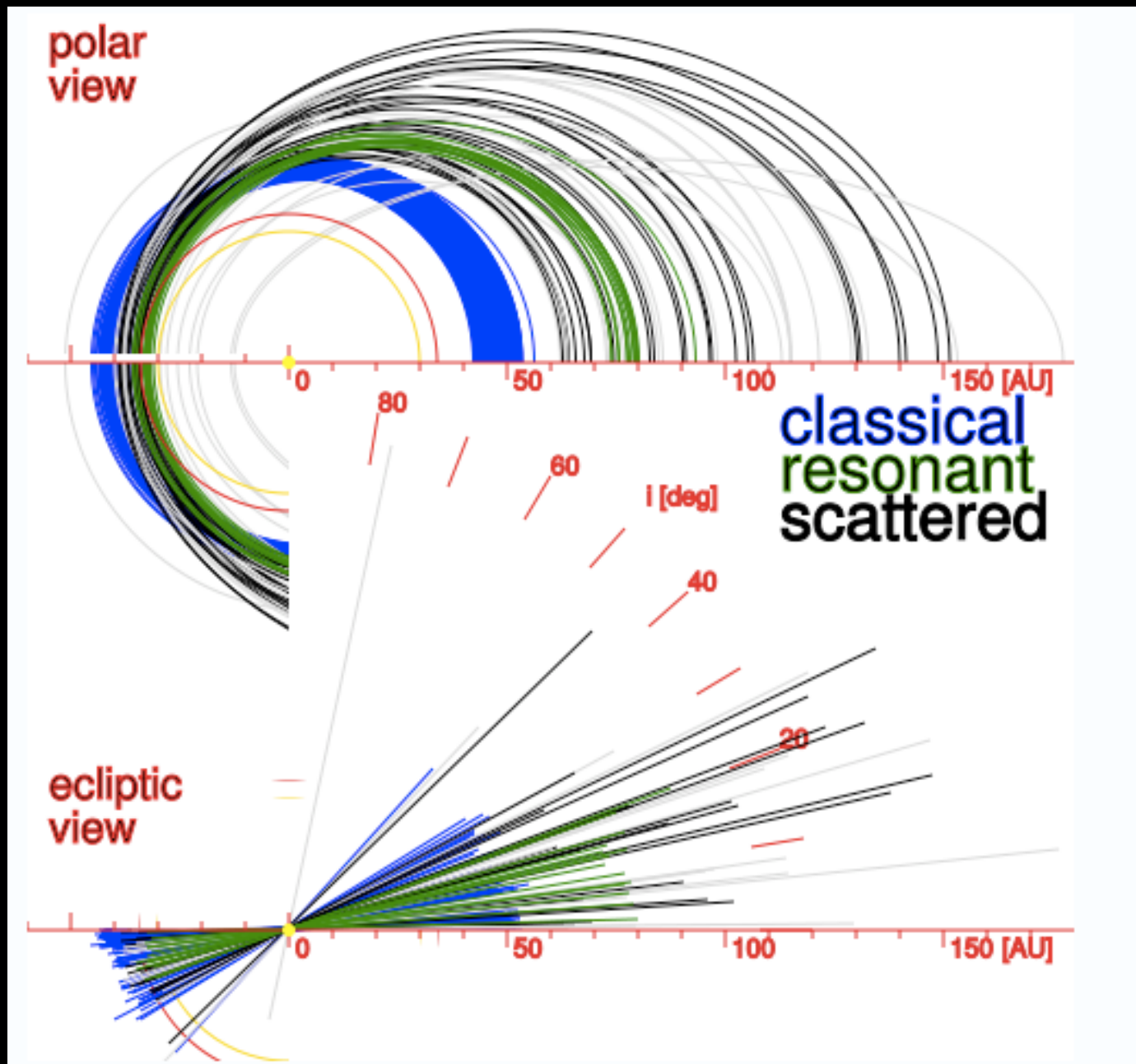
- *Plutinos*, which are in 3:2 resonance with Neptune: these form the inner part of the Kuiper belt; e.g. Pluto
- *Classical Kuiper belt objects* (also called *cubewanos*), which are beyond Neptune but not in a resonance; e.g. 1992 QBI, Quaoar, Varuna
- *Scattered disc objects*, which are in larger and 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.



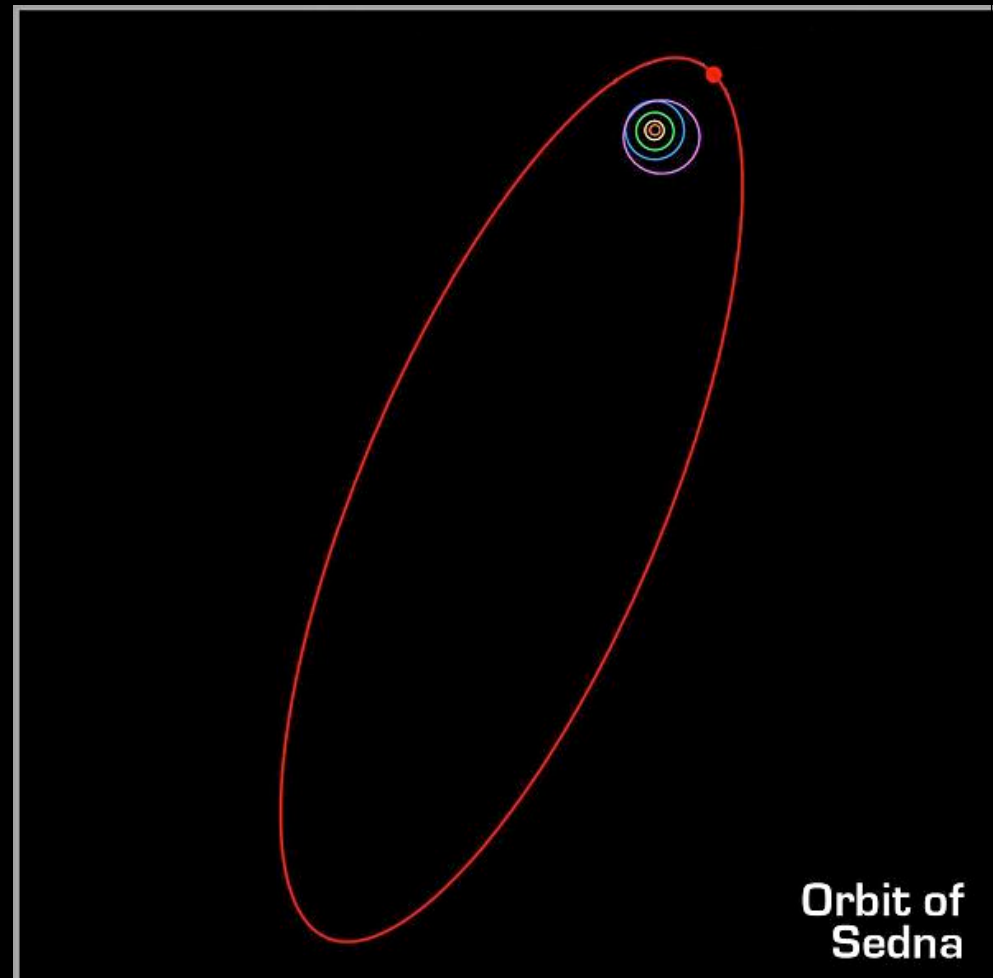
Small solar-system bodies. Resonance objects are shown in red, Kuiper Belt objects in blue, and scattered disk objects in grey.



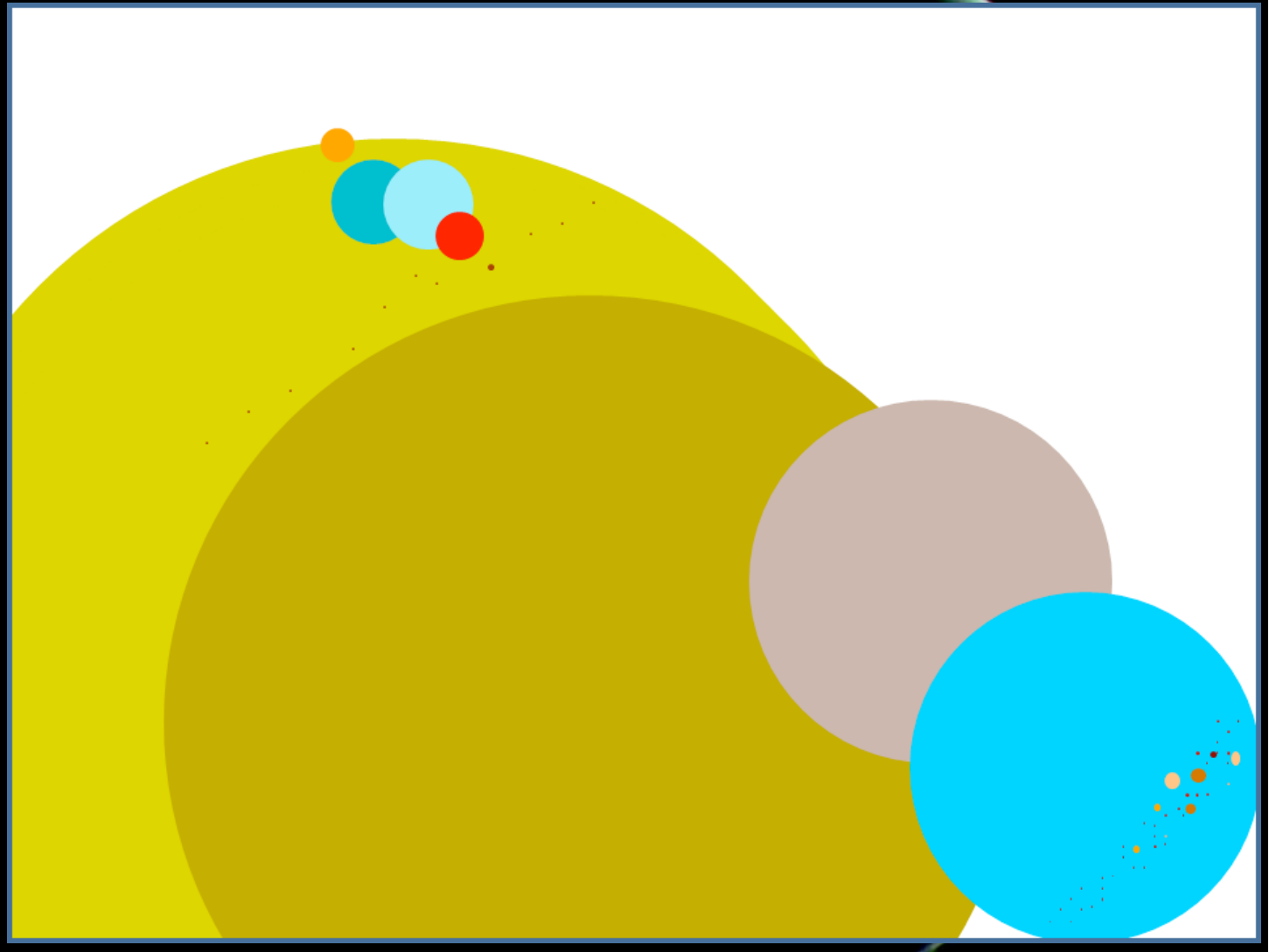
Orbits of the cubewanos (blue), resonant (green) and scattered disk objects, from above and side-on. Yellow represents Neptune's orbit.

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.

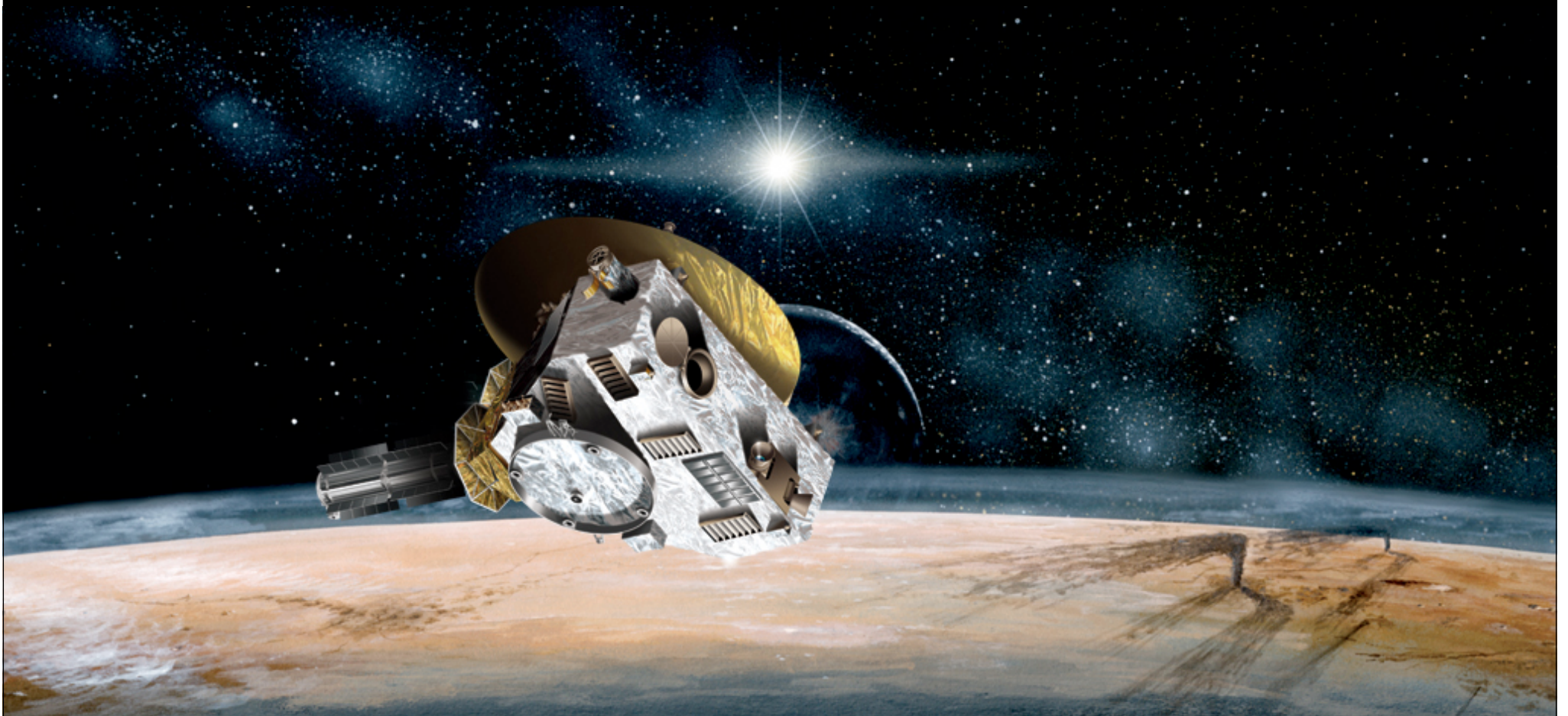
Sedna's orbit is very hard to explain. It must have been pulled into its current orbit by gravitational interaction with another body: another star, or possibly a Neptune-mass planet in the Oort cloud.

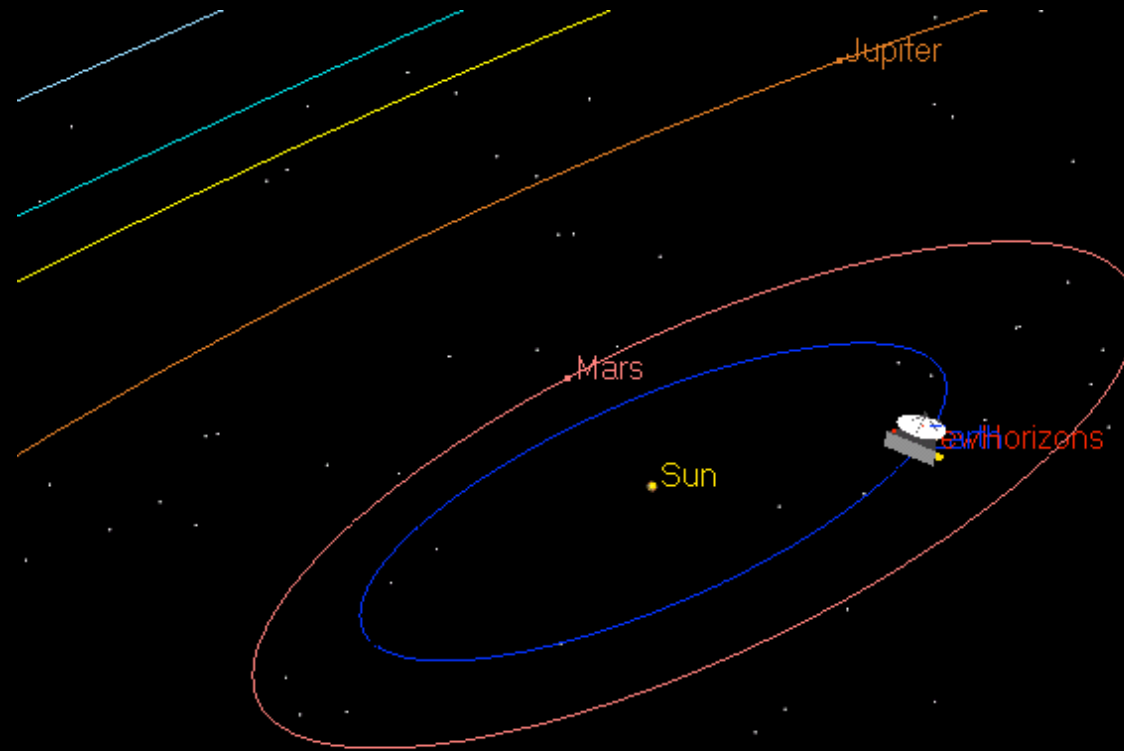


Mike Brown (discoverer of Eris) has made an image showing the relative sizes of the planets, in a way which makes it clear why the demotion of Pluto was correct.



The New Horizons mission to Pluto and the Kuiper Belt was launched on 19 January 2006. The Jupiter flyby in February 2007 gave it a gravity assist, and it is currently in its “interplanetary cruise” phase, awaiting the Pluto-Charon flyby in July 2015. It passed Uranus’ orbit in March this year.

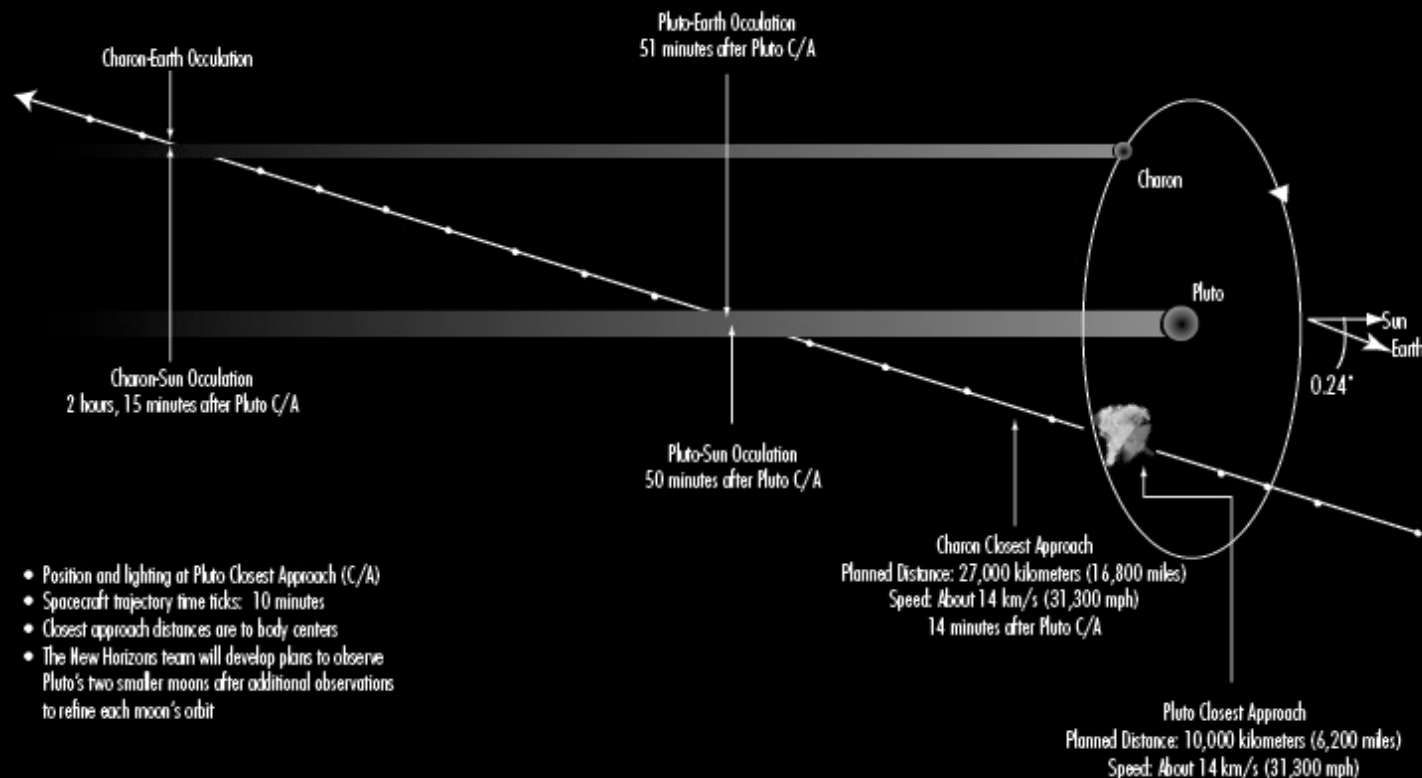




After flying past Pluto and Charon, the plan is to travel on past at least one Kuiper Belt object, as yet unidentified.

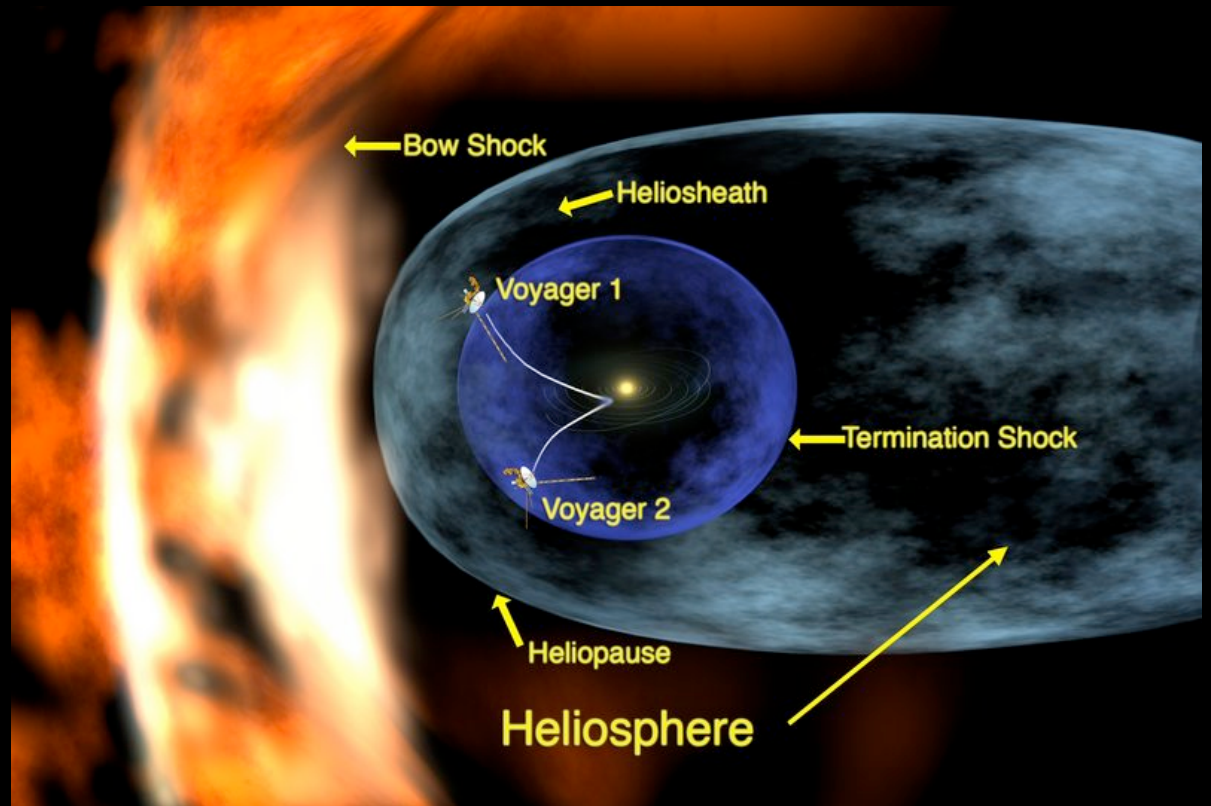
Like Voyager at Uranus and Neptune, New Horizons will have very little time to study Pluto and Charon during its flyby.

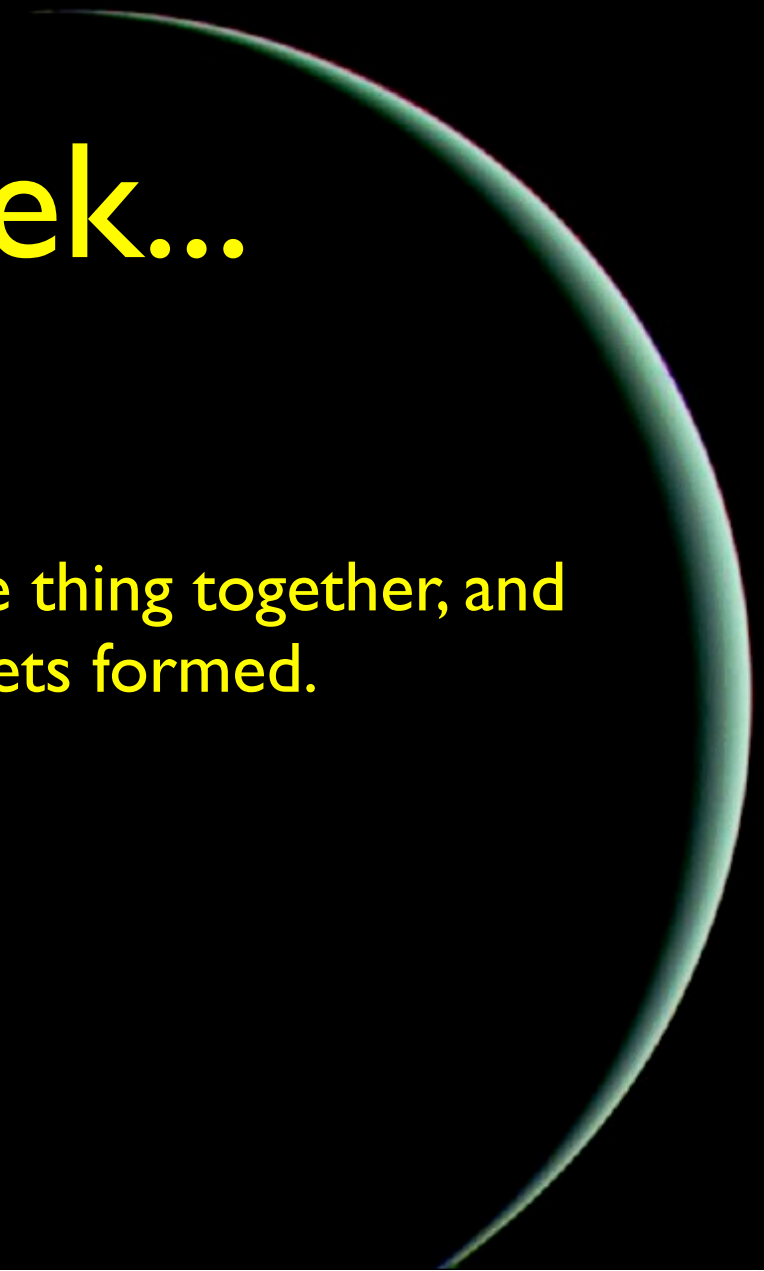
Pluto-Charon Flyby: Closest Approach (July 2015)



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 5–10 years it should cross the heliopause and enter interstellar space.

In August 2006, Voyager 1 reached a distance of 100 AU from the Sun. It could continue to operate until 2020.





Next week...

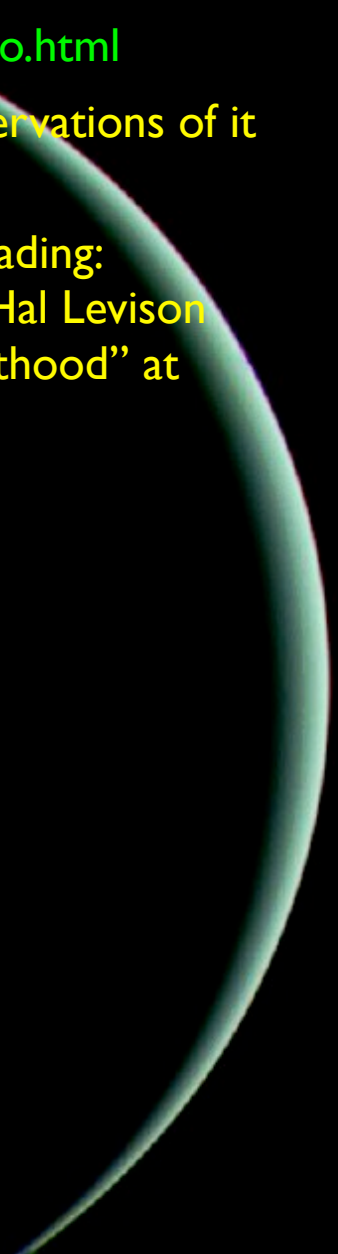
... we're going to tie the whole thing together, and
look at how the planets formed.

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 will fly by 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://www.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>



Sources for images used:

- Background image: parting image taken by Voyager 2, PIA00143 <http://photojournal.jpl.nasa.gov/catalog/PIA00143>
- 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: from NSSDC Photo Gallery: Uranus http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-uranus.html
- 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://antwarp.gsfc.nasa.gov/apod/ap041118.html>
- Seasons: from Astronomy 121: The Solar System by Jim Brau http://blueox.uoregon.edu/~courses/Braulimages/Chap13/FG13_006.jpg
- 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
- Dark cloud: Hubblesite release STScI-2006-47 <http://hubblesite.org/newscenter/archive/releases/2006/47/>
- Interior: from Views of the Solar System by Calvin J. Hamilton <http://www.solarviews.com/browse/uranus/uranusint.jpg>
- Storms on Uranus: from Hubble Site News Release Archive, March 29 1999, "Huge Spring Storms Rouse Uranus from Winter Hibernation" <http://hubblesite.org/newscenter/archive/1999/11/>
- 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
- HST image of rings and moons: from Astronomy Picture of the Day 26 November 1997 <http://antwrp.gsfc.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 Views of the Solar System by Calvin J. Hamilton <http://www.solarviews.com/eng/uranus.htm>
- 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>
- Discovery position of Neptune: from http://www-history.mcs.st-andrews.ac.uk/HistTopics/Neptune_and_Pluto.html
- Galileo's drawing: from Standish & Nobili, "Galileo's observations of Neptune", Baltic Astronomy, 6, 97 (1997) <http://adsabs.harvard.edu/abs/1997BaltA...6...97S>
- Neptune and Uranus compared: <http://astsun.astro.virginia.edu/~mnc3z/astro121.html>
- Full disk of Neptune: Voyager image, from Views of the Solar System by Calvin J. Hamilton <http://www.solarviews.com/cap/nep/neptunes.htm>
- Atmosphere images: from Views of the Solar System by Calvin J. Hamilton <http://www.solarviews.com/cap/index/neptune.html>
- Time-lapse movie of Neptune's weather: from HST news release archive, "Hubble Makes Movie of Neptune's Rotation and Weather", October 24 1996, <http://hubblesite.org/newscenter/archive/1996/33/>
- Interiors and magnetic fields: from "Planets, Stars and Galaxies" by Todd Adams, www.hep.fsu.edu/~tadams/courses/fall02/ast1002/lectures/Lecture092502.pdf
- 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>
- Orbits of Triton and Nereid: re-drawn from "Atlas of Uranus" by Garry Hunt and Patrick Moore (Cambridge UP, 1989), p. 50
- New moons of Neptune: from CfA Press Release No.: 03-03, "New Moons Found Around Neptune" <http://cfa-www.harvard.edu/press/pr0303.html>

- Moon collision: painting by Don Davis, from http://www.universetoday.com/am/publish/pluto_3_moons.html
- Binary capture of Triton: from Alessandro Morbidelli, "Interplanetary kidnap", Nature, 441, 162 (2006)
- Artist's conception of Pluto and Charon: from Astronomy Picture of the Day 2001 October 18
<http://antwrp.gsfc.nasa.gov/apod/ap011018.html>
- HST image of Pluto/Charon: from Astronomy Picture of the Day 13 February 1999
<http://antwrp.gsfc.nasa.gov/apod/ap990213.html>
- 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>
- Charon's orbit: from Pluto Home by Paul McGehee, <http://dosxx.colorado.edu/Pluto/pluto1.html>
- Mutual eclipses: from Pluto Home by Paul McGehee, <http://dosxx.colorado.edu/Pluto/pluto2.html>
- Colour image of Pluto: from "Mapping Pluto's Surface" by Eliot Young
<http://www.boulder.swri.edu/~efy/PMap01/PlutoMaps/PlutoMaps.html>
- Pluto animation: from Hubble News Release Archive, 7 March 1996, "Hubble Reveals Surface of Pluto for First Time"
<http://hubblesite.org/newscenter/archive/1996/09/>
- Artist's impression of Pluto/Charon: Fahad Sulehria http://www.novacelestia.com/images/space_art_pluto_charon.jpg
- Pluto's moons: <http://apod.nasa.gov/apod/ap060624.html> and http://science.nasa.gov/science-news/science-at-nasa/2011/20jul_p4/
- New Horizons image and animation: from "New Horizons: NASA's Pluto-Kuiper Belt mission"
<http://pluto.jhuapl.edu/index.php>
- Eris images: Michael Brown: The discovery of 2003-UB313 Eris, the 10th planet largest known dwarf planet
<http://www.gps.caltech.edu/~mbrown/planetlila/>
- Eris orbit: Wikipedia [http://en.wikipedia.org/wiki/Eris_\(dwarf_planet\)](http://en.wikipedia.org/wiki/Eris_(dwarf_planet))
- Mike Brown's "Planetary placemat" <http://www.mikebrownplanets.com/2009/08/planetary-placemats.html>
- Voyagers entering the solar heliopause: from "Voyager Enters Solar System's Final Frontier",
http://www.nasa.gov/vision/universe/solarsystem/voyager_agu.html