Uranus and Neptune

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Glossary

Diapir Is an upwelling of material, or intrusion, moving into overlying surface. They follow Rayleigh-Taylor instability patterns (mushroom or dikes shapes) depending on the tectonic environment and density contrast between the intrusion material and the surface.

Geometric Albedo Brightness of a planet or satellite measured at null solar phase angle ratioed to that of a lambertian (ideal fully reflective) surface with the same dimension. For surfaces made up of small water ice grains the geometric albedo can be >1, meaning that the surface is more efficient than an ideal lambertian surface in scattering back the received light.

Hydrostatic equilibrium A body reaches hydrostatic equilibrium when it assumes spherical (or ellipsoid) shape under its own gravity. This condition happens when gravity is balanced by pressure. About 30 objects in the Solar System are known to be in hydrostatic equilibrium and this criterion is currently used to distinguish dwarf planets from small bodies.

Leading hemisphere The hemisphere of a satellite that faces into the direction of motion. This applies to satellites in synchronous orbits, thus always keeping the same face towards the planet.

Optical depth This is a measure of the transparency of a ring system. A large optical depth indicates an opaque ring for which a small amount of light is able to pass through without being reflected or absorbed.

Trailing hemisphere The hemisphere of a satellite that faces away from the direction of motion. This applies to satellites in synchronous orbits, thus always keeping the same face towards the planet.

Introduction

Uranus

Uranus was discovered by William Herschel in March 1781 with telescopic observations and, so far, has been explored only by the Voyager 2 spacecraft during its fly by on January 24, 1986. The planet orbits at an average distance from the Sun of 19.2 AU in 84 years. Uranus has a radius of 25,362 km (about four times the radius of Earth) and has a density of 1.27 g/cm^3. After Saturn, Uranus is the second least dense planet in our Solar System. This suggests the presence of an inner nucleus made mainly of ices like water, ammonia, methane, which accounts for about 9–13 Earth masses and a small quantity of rocky material representing 0.5–1.5 Earth masses. The gaseous fraction, made up of hydrogen and helium, accounts for the remaining 0.5–1.5 Earth masses and forms the gaseous atmosphere that envelops the planet. Uranus, like Neptune, differs from Saturn and Jupiter in that ices rather than gases dominate their interiors. For this reason they are called "ice giants" rather than "gas giants." As a consequence of the ice-rich nucleus, the planet has a low inner thermal flux (smaller than the Earth's), which explains the low temperature of 49 K (−224°C) measured in the tropopause. Uranus' atmosphere is mainly made of hydrogen (82.5%), helium (15.2%) and methane (2.3%). Methane molecules preferentially absorb red light, causing the characteristic pale blue color of the planet at visible wavelengths. The atmosphere appears remarkably featureless (Fig. 1): sometimes layered cloud structures appear, showing condensation of water ice in the lowest cloud deck and methane ices in the uppermost. Solar UV radiation is able to dissociate methane, resulting in the formation of hydrocarbons (ethane, acetylene) observed in traces in the upper atmosphere. Uranus, having a geometric albedo of 0.3, is much less bright than the other outer solar system planets like Jupiter (0.52), Saturn (0.47) and Neptune (0.44). The atmospheric dynamics are driven by the peculiar state of the rotation axis of the planet, which is tilted about 98 degrees. As a consequence of this effect, one hemisphere is oriented towards the Sun for half of the orbital period, causing a 42 year-long day on the pole. Meanwhile, the other hemisphere is in permanent night for the same period of time. Only at equinox, every 42 years, when the Sun crosses Uranus' equator, the night-day period corresponds to the rotational period of the planet (17 h 14 min). Another peculiar aspect of Uranus is its dipole magnetic field, tilted by about 60 degrees with respect to the rotation axis and not centered on the center of mass of the planet. These properties, together with the rotation axis tilt, cause a strong asymmetry in the magnetic field.

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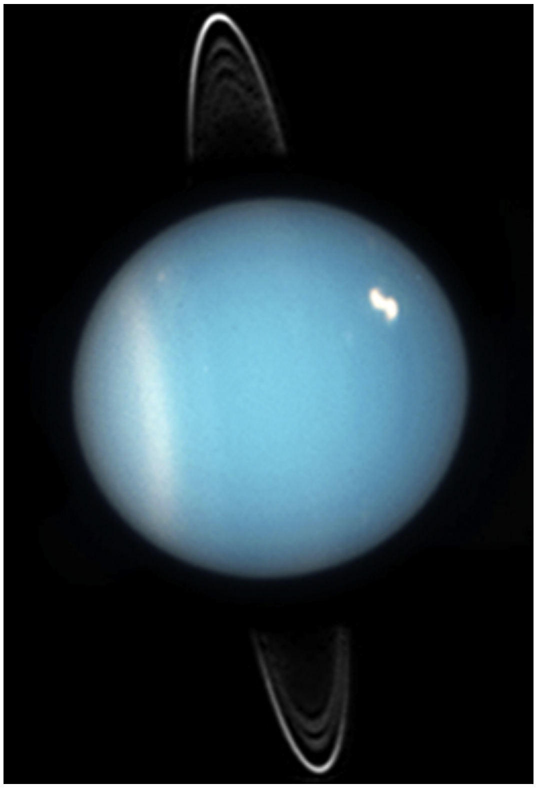

Fig. 1 Uranus observed by Hubble Space Telescope in 2005, 2 years before autumnal equinox (2007). Rings, southern hemisphere bright collar and a cloud in the northern hemisphere are visible (HST ACS image). Public domain image by NASA, ESA, and M. Showalter (SETI Institute)—http://hubblesite.org/newscenter/archive/releases/2007/32/image/c/

During Voyager 2 fly by the onboard magnetometer measured an more intense magnetic field on the northern (dayside) hemisphere than on the southern (nightside).

Weak auroral emissions, observed by Hubble Space Telescope, are caused by the interaction of solar wind with the planet's ionosphere.

Uranus is also characterized by a complex system of satellites and rings: these are described in sections "Satellites" and "Rings," respectively.

Neptune

Neptune was discovered in 1846 by J. Galle and H. D'Arrest from the Berlin observatory. The discovery was made on the basis of trajectory predictions of a new planet based on perturbations observed on Uranus positions made by French mathematician U. J. J. Le Verrier.

Neptune orbits at about 30 AU from the Sun in 164.8 years. Like Uranus, the only spacecraft able to reach it was Voyager 2 in 1989. A few days before its closest approach, the camera onboard the spacecraft captured the color image shown in Fig. 2. Like Uranus, Neptune is also an ice giant with a bluish atmosphere, mainly made of hydrogen and helium with smaller quantities of methane, hydrogen cyanide, acetylene and ethane. In contrast to Uranus, Neptune's atmosphere appears very active and rich in structures. Bright clouds made by ices, including cirrus clouds, and a Great Dark Spot were made visible by Voyager 2 images. The Great Dark Spot was a huge oval anti-cyclonic structure (13,000 × 6600 km along major axes) rotating counterclockwise and with a vortex structure. This area of high pressure was slowly drifting with respect to the nearby clouds and it later disappeared on images taken by the Hubble Space Telescope. Another similar storm, called the Small Dark Spot, as well as bright clouds of ammonia and hydrogen sulfide were also visible in Voyager 2 images.

The dynamic evolution of Neptune's atmosphere is caused by the strong (compared to Uranus) heat flux from the interior. The planet radiates 2.6% more energy than it receives from the Sun. Having a radius of 24,662 km, Neptune is slightly smaller than Uranus but it is much denser (1.638 g/cm^3). Higher density and heat flux are a consequence of a larger icy nucleus. The planet rotates in 16 h 6 min around an axis tilted by 28.32 degrees with respect to the orbital plane. The magnetosphere of Neptune is quite

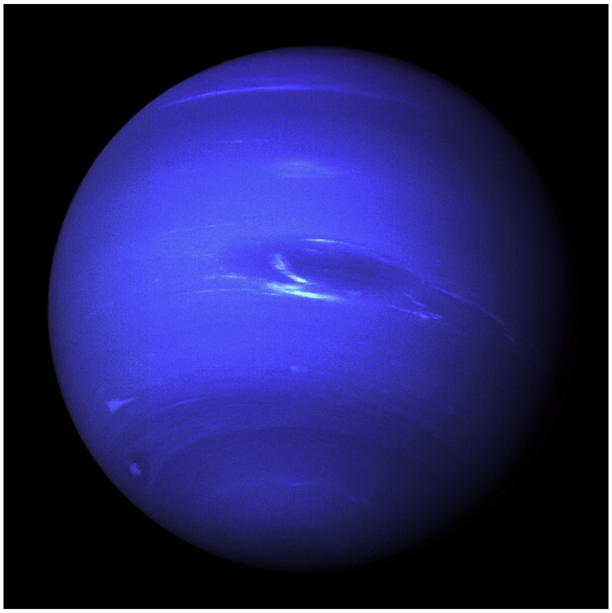

Fig. 2 Neptune as seen by Voyager 2 in August 1989. On the center of the planet the Great Dark Spot and its companion bright smudge are visible; the fast moving bright cloud called Scooter and the little dark spot are on the on the left limb. Public domain image, courtesy NASA/JPL.

complicated because, apart from the dipole moment which is offset with respect to center of mass and tilted by 47 degrees from the rotation axis, it has an intense quadrupole moment, exceeding the dipole in strength.

Like Uranus, Neptune is escorted by numerous satellites and has a system of rings, which are described in sections "Satellites" and "Rings", respectively.

Satellites

Both Uranus and Neptune host numerous satellites, including regular moons, external irregulars and inner small moons connected with the planets' rings. The orbital and physical parameters of the Uranus and Neptune satellites are listed in Tables 1 and 2, respectively.

The five major regular satellites of *Uranus* (Miranda, Ariel, Umbriel, Titania, Oberon) are sufficiently large (radii between 471 km for Miranda and 1576 km for Titania) to be in hydrostatic equilibrium. Their surfaces indicate the presence of internal processes (volcanism, tectonic activity), resulting in the formation of high cliffs, fault valleys, fractures and trench-like features. With the exception of *Miranda* (Fig. 3), which is characterized by a low-density (1.2 g/cm^3) and is made mainly of ices, the bulk composition of the other regular moons is represented by denser (1.4–1.7 g/cm^3) mixtures of rock and ices (carbon dioxide, ammonia) in equal proportions. Evolution models suggest that these satellites have collected material orbiting within an accretion disc shortly after Uranus' formation. The surfaces of all these satellites show evidence of endogenic resurfacing and tectonic phenomena, causing a rich geologic environment.

Among them, Miranda certainly shows the roughest topography, including Verona Rupes, a 20 km-high cliff visible on the bottom limb of Fig. 3, and circular-shaped coronae, probably formed by diapirs (warm ice upwelling). These features are remarkably large with respect to the dimensions of the moon. Extensional tectonic movements have formed numerous canyons (hundreds of km-long and tens of km-wide) crisscrossing the surface, while impact craters show both very ancient and recent origins. This complex morphology is further evidence of a past resurfacing event caused by the intense heating released when the moon was in 3:1 orbital resonance with Umbriel. It is known, in fact, that resonances are able to increase the orbital eccentricity of the inner moon, contributing to its internal heating by tidal forces, the main source of the geological activity. The current dayside temperature on Miranda is 85 K (−188°C).

Also *Ariel*'s surface (Fig.4, *top left*) is characterized by a complex geology showing an extensive system of canyons, chasmata (a deep, steep-sided depression), scarps and ridges overlying cratered terrains. These morphological features allow the classification of the surface into three groups: old cratered terrains, ridged terrains and young smooth plains. Dynamic models suggest that in the past Ariel experienced several orbital resonances (4:1 with Titania, 5:3 with Miranda) causing tidal heating and warming of the interior. This resulted in the insurgence of resurfacing and tectonic phenomena. Surface infrared spectroscopy has revealed a diffuse presence of water ice while carbon dioxide ice is mainly observed on the trailing hemisphere. Since Ariel's orbit is within the Uranus

Table 1 Uranian moons physical parameters. Negative orbital period indicates a retrograde orbit.

Moon	*Diameter (km)*	*Mass (10^{18} kg)*	*Semimajor axis (km)*	*Orbital period (day)*	*Orbital inclination (degree)*	*Eccentricity*	*Geometric Albedo*
Cordelia	50×36	0.044	49,770	0.335	0.085	0.000,26	0.08
Ophelia	54×38	0.053	53,790	0.376	0.104	0.009,92	0.08
Bianca	64×46	0.092	59,170	0.435	0.193	0.000,92	0.08
Cressida	92×74	0.34	61,780	0.464	0.006	0.000,36	0.08
Desdemona	90×54	0.18	62,680	0.474	0.111	0.000,13	0.08
Juliet	150×74	0.56	64,350	0.493	0.065	0.000,66	0.08
Portia	156×126	1.70	66,090	0.513	0.059	0.000,05	0.08
Rosalind	72 ± 12	0.25	69,940	0.558	0.279	0.000,11	0.08
Cupid	≈ 18	0.0038	74,800	0.618	0.1	0.001,3	0.07
Belinda	128×64	0.49	75,260	0.624	0.031	0.000,07	0.08
Perdita	30 ± 6	0.018	76,400	0.638	0.0	0.001,2	0.08
Puck	162 ± 4	2.90	86,010	0.762	0.319	0.000,12	0.11
Mab	≈ 25	0.01	97,700	0.923	0.133	0.002,5	0.10
Miranda	$481 \times 468 \times 466$	65.9 ± 7.5	129,390	1.413	4.232	0.001,3	0.32
Ariel	$1162 \times 1156 \times 1155$	1353 ± 120	191,020	2.520	0.260	0.001,2	0.53
Umbriel	1169.4 ± 5.6	1172 ± 135	266,300	4.144	0.205	0.003,9	0.26
Titania	1576.8 ± 1.2	3527 ± 90	435,910	8.706	0.340	0.001,1	0.35
Oberon	1522.8 ± 5.2	3014 ± 75	583,520	13.463	0.058	0.001,4	0.31
Francisco	≈ 22	0.0072	4,276,000	−266.56	147.459	0.145,9	0.04
Caliban	≈ 72	0.25	7,230,000	−579.50	139.885	0.158,7	0.04
Stephano	≈ 32	0.022	8,002,000	−676.50	141.873	0.229,2	0.04
Trinculo	≈ 18	0.0039	8,571,000	−758.10	166.252	0.220,0	0.04
Sycorax	≈ 165	2.30	12,179,000	−1283.4	152.456	0.542,4	0.049
Margaret	≈ 20	0.0054	14,345,000	1694.8	51.455	0.660,8	0.04
Prospero	≈ 50	0.085	16,418,000	−1992.8	146.017	0.444,8	0.04
Setebos	≈ 48	0.075	17,459,000	−2202.3	145.883	0.591,4	0.04
Ferdinand	≈ 20	0.0054	20,900,000	−2823.4	167.346	0.368,2	0.04

Table 2 Neptunian Moons physical parameters. Negative orbital period indicates a retrograde orbit.

Moon	*Diameter (km)*	*Mass (10^{16} kg)*	*Semi-major axis (km)*	*Orbital period (day)*	*Orbital inclination (degrees)*	*Eccentricity*	*Geometric Albedo*
Naiad	$96 \times 60 \times 52$	≈ 19	48,227	0.294	4.691	0.000,3	0.07
Thalassa	$108 \times 100 \times 52$	≈ 35	50,074	0.311	0.135	0.000,2	0.09
Despina	$180 \times 148 \times 128$	≈ 210	52,526	0.335	0.068	0.000,2	0.09
Galatea	$204 \times 184 \times 144$	≈ 375	61,953	0.429	0.034	0.000,1	0.08
Larissa	$216 \times 204 \times 168$	≈ 495	73,548	0.555	0.205	0.001,4	0.09
S/2004 N1	≈ 20	$\approx 0.5 \pm 0.4$	$105{,}300 \pm 50$	0.936	0.000	0.0	unknown
Proteus	$436 \times 416 \times 402$	≈ 5035	117,646	1.122	0.075	0.000,5	0.096
Triton	$2709 \times 2706 \times 2705$	$2{,}140{,}800 \pm 5200$	354,759	−5.877	156.865	0.0	0.76
Nereid	$\approx 340 \pm 50$	≈ 2700	5,513,818	360.13	7.090	0.750,7	0.155
Halimede	≈ 62	≈ 16	16,611,000	−1879.08	134.1	0.264,6	0.04
Sao	≈ 44	≈ 6	22,228,000	2912.72	49.907	0.136,5	0.04
Laomedeia	≈ 42	≈ 5	23,567,000	3171.33	34.049	0.396,9	0.04
Psamathe	≈ 40	≈ 4	48,096,000	−9074.30	137.679	0.380,9	0.04
Neso	≈ 60	≈ 15	49,285,000	−9740.73	131.265	0.571,4	0.04

magnetosphere, the trailing hemisphere collects more cold plasma particles trapped in the magnetic field than the leading hemisphere. A similar process is able to synthesize CO_2 ice from water ice and carbonaceous material.

With a value of 0.53, Ariel's albedo is the highest among the Uranian satellites.

Umbriel is the same size as Ariel, it has a lower density (1.39 g/cm^3) pointing to a greater abundance of ices. Despite this, Umbriel is the darkest among the regular satellites of Uranus, with a geometric albedo of 0.26, half that of Ariel. Voyager 2 images (Fig. 4, *top right*) show a dark surface with a prominence of impact craters, ranging in size from a diameter of a few kilometers up to 200 km, many of them with central peaks. The surface appears to be covered by a layer of dark material covering the underlying ices. The source of this material is probably the outer irregular satellites. The large Wunda crater is visible at the north pole, characterized by

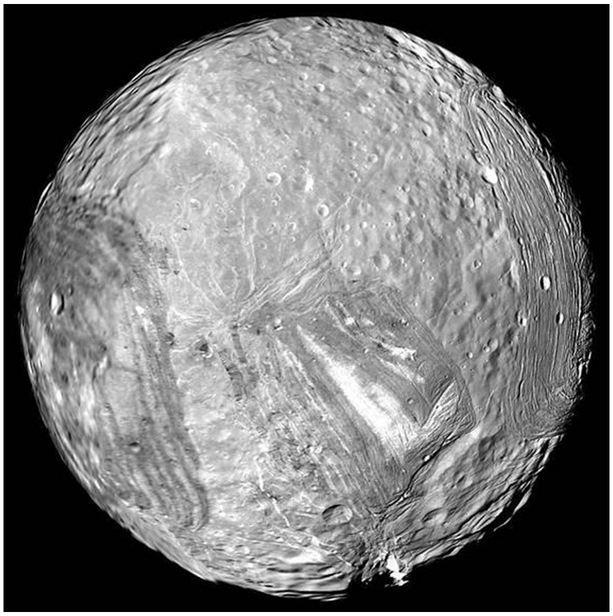

Fig. 3 Surface of Miranda's south hemisphere, one of the regular moons of Uranus. Photomosaic obtained from Voyager 2 images taken on January 24, 1986. Public domain image, courtesy by NASA/JPL.

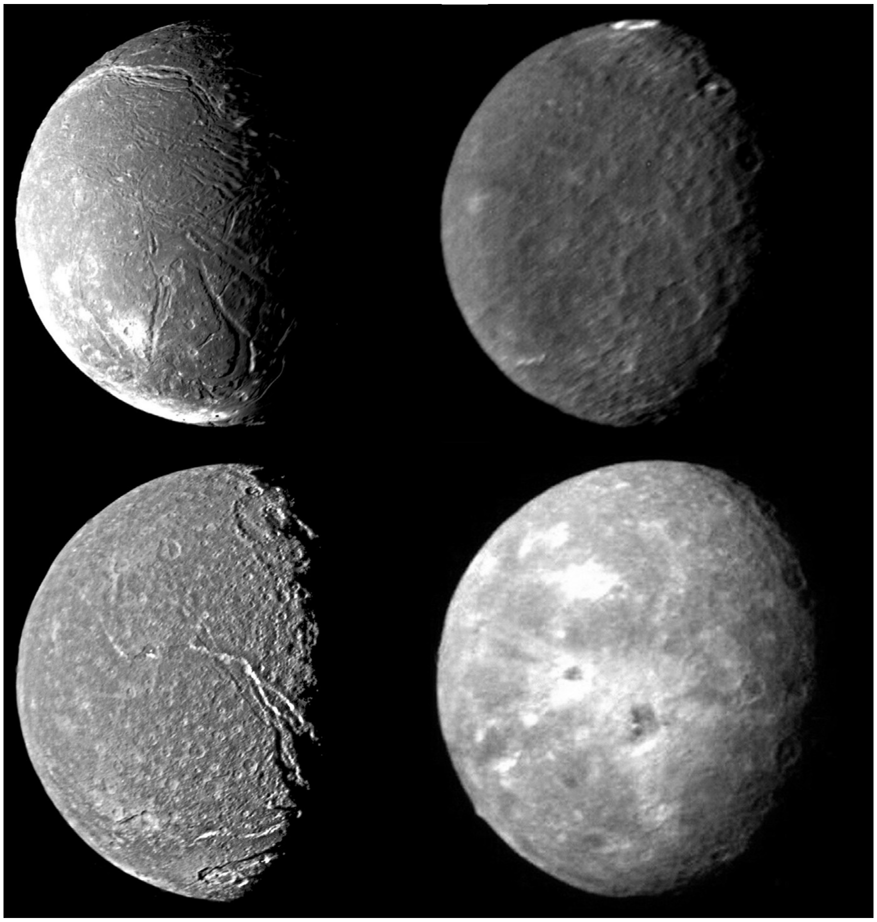

Fig. 4 Ariel, Umbriel, Titania and Oberon (from *top left* to *bottom right*) as imaged by Voyager 2 camera. Public domain images courtesy by NASA/JPL.

bright floor and walls. This is probably the result of local condensation of CO_2 ice or by insufficient mantling of exogenous dark material.

Titania is the largest (diameter 1576 km) and densest (1.71 g/cm^3) satellite of Uranus. Voyager images (Fig. 4, *bottom left*) of the surface show three morphological units: cratered terrains, canyons and scarps. The percentage of the cratered surface is lower than on Oberon and Umbriel, suggesting a more recent evolution. Craters reach considerable dimensions in relation to the size of the moon: crater Gertrude is 320 km wide. Canyons are another remarkable characteristic of Titania's surface, scarring large extensions of the surface. Messina Chasmata, the larger canyon, has a width of about 50 km, a height of 5 km, and runs for about 1500 km from equator to the south pole region. Scarps and rupes (steep, high rock faces) are relatively smooth regions related with the resurfacing of material from the interior (cryovolcanism).

The outermost regular satellite of Uranus is *Oberon* (Fig. 4, bottom right), the second most massive of the family and the one with the reddest colors. In particular, the leading hemisphere of the moon contains more red and dark material than the trailing hemisphere as a consequence of the deposition of exogenous particles, probably released by the outer irregular satellites. A similar mechanism occurs on Saturn's moon Iapetus that collects dust coming from Phoebe. The surface of Oberon shows a smaller system of chasmata, indicating that internal heating causes the tectonic stresses on this satellite. Some models explain the presence of chasmata by the presence of a liquid layer situated at the interface between the inner core and the mantle. Oberon's surface appears very old, as it is the most cratered among the Uranian moons. The craters include both rayed craters and large basins with dark material deposits on their floors.

A total of 13 *inner moons* are located inside the orbit of Miranda. The outermost of them are Puck (162 km in diameter, the largest inner moon) and Mab (25 km in diameter). The latter orbits within the outer μ ring. Cordelia and Ophelia are ε ring shepherd moons, orbiting inside and outside it, respectively. Four other small moons (Bianca, Cressida, Desdemona, Juliet) orbit between ε and *ν* rings (see Fig. 6). Portia and Rosalind are probably shepherd moons of the ν ring. Finally, a group of small (≈100 km) satellites, including Cupid, Perdita, and Belinda, are placed between the ν ring and Puck.

These objects were largely unexplored by Voyager 2. Earth observations are difficult due to their small sizes. Their surfaces show low albedo (≈0.1) as a consequence of the presence of dark material, perhaps dust or organic matter processed by radiation. The orbits of the inner moons are chaotic, possibly indicating past collisions among them, and causing the formation of the nearby dusty rings.

Finally, a system of nine *irregular moons*, with diameters from a few tens to hundreds of km, have been observed beyond Oberon's orbit. The innermost is Francisco, with a semimajor axis of 4,276,000 km while Ferdinand, at 20.9 million km, is the outermost. These are certainly captured objects as evidenced by their retrograde and very inclined orbital planes.

Two families of moons are observed in the *Neptune* system: regular and irregular (Table 2). The six inner regular moons, in order of distance from Neptune, are Thalassa, Despina, Galatea, Larissa, S/2004 N1 and Proteus. All of these objects have small sizes ($20 \leq$ diameter ≤ 200 km) with the exception of the outer one, *Proteus*, which is the second largest moon of Neptune (diameter ≈400 km). Voyager 2 images show a polyhedron-shaped surface, heavily cratered and with many scarps and grooves. At 230 km in diameter, Pharos is the largest impact crater visible on the dark (albedo ≈0.1) surface of the moon. The irregular shape indicates that the moon has not reached hydrostatic equilibrium, suggesting that it was probably formed from accretion of debris. Spectral measurements show a quite gray visible and near infrared reflectance spectrum typical of organic compounds (hydrocarbons, cyanides), mixed with ices and dust. Irregular satellites orbit in the outer part of the Neptune system. The more remarkable among them are Triton and Nereid. *Triton* is the brightest (albedo 0.76) satellite. With a diameter of 2700 km it is the largest satellite of Neptune and is larger than any satellite of Uranus. The moon rotates on a retrograde orbit of 355,000 km from Neptune and has a very high orbital inclination (156.8 degrees). These characteristics make Triton a captured, high mass object. Apart from this anomalous property, Triton has other very peculiar features. It is one of the coldest satellites in our solar system, having a surface temperature of −235°C, (only 18°C above absolute zero). These low temperatures allow the condensation of very volatile chemical species, such as nitrogen, ammonia, and methane, which have been observed, mixed with water ice, on Triton's surface. Moreover, Triton shows little surface relief and only a few, small impact craters (Fig. 5). The moon's south polar region is dominated by "pink" ice, made from a mixture of nitrogen, methane and ammonia. Several geysers are active in this area, sustained by liquid nitrogen reservoirs in the subsurface. Other remarkable areas are Monad Regio, a feature that is half smooth and half hummock, with rimless pits (paterae), mushroom-like features (guttae) and low-walled plains. Bubembe Regio is a feature characterized by so-called "cantaloupe" terrain (because it is similar to the texture of melon-rind) made by a mixture of ancient and dirty water and nitrogen ice. Many sulci, fractures and tectonic faults zigzag across the surface and meet at elevated X or Y-shaped junctions. The sublimation of volatile chemicals and geyser emissions are the sources of the tenuous atmosphere made of nitrogen with traces of methane gases.

Nereid is on a very elliptical orbit (1.35–9.62 million km), and is the second largest Neptune satellite (340 km diameter). The high orbital eccentricity and direct motion indicate that it is probably an inner satellite perturbed during Triton's capture. The moon shape is still uncertain but few large impact craters are visible on its surface. Nereid visible color is almost neutral and shows water ice spectral signatures.

Rings

All giant planets are circled by planetary rings, but the *Uranus ring system* is very different from those of Jupiter and Saturn. This consists of 11 single ringlets (named 6, 5, 4, α, β, η, γ, δ, ε, *ν*, μ) and two dust diffuse rings (named λ and ζ, see Table 3). Their composition is still uncertain but the low albedo (0.05) suggests that in contrast to Saturn's rings, they are not dominated by water

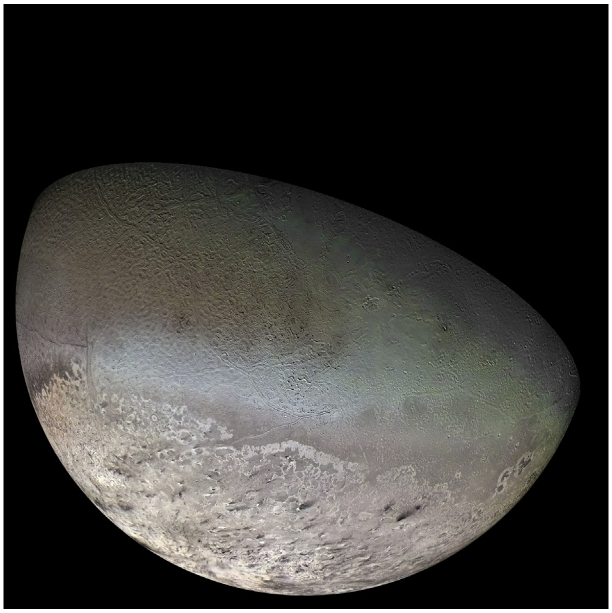

Fig. 5 Photomosaic of Triton returned by Voyager 2. The south polar region is on the bottom of the image where active geysers are visible. The dark streaks near active geysers are dust deposits. Equatorial area is on the top of the image where the cantaloupe terrains are located. Public domain image from NASA/JPL.

Table 3 Uranus rings properties.

Ring	*Radius (km)*	*Width (km)*	*Optical depth*
ζ_{cc}	26,840–34,890	8000	≈0.001
ζ_c	34,890–37,850	3000	≈0.01
1986U2R	37,000–39,500	2500	<0.01
ζ	37,850–41,350	3500	≈0.01
6	41,837	1.6–2.2	0.18–0.25
5	42,234	1.9–4.9	0.18–0.48
4	42,570	2.4–4.4	0.16–0.30
α	44,718	4.8–10.0	0.3–0.7
β	45,661	6.1–11.4	0.20–0.35
η	47,175	1.9–2.7	0.16–0.25
η_c	47,176	40	0.2
γ	47,627	3.6–4.7	0.7–0.9
δ_C	48,300	10–12	0.3
δ	48,300	4.1–6.1	0.3–0.6
λ	50,023	1–2	0.1–0.2
ε	51,149	19.7–96.4	0.5–2.5
ν	66,100–69,900	3800	0.000,054
μ	86,000–103,000	17,000	0.000,085

ice but rather by dust particles. Moreover, their orbits are characterized by eccentricity and inclination. They have very sharp boundaries, caused by the gravitational confinement of nearby small moons (Fig. 6, *left panel*): rings ζ, 6, 4, α, η, γ, δ are in fact within Cordelia's orbit; λ and ε, the brightest ring thanks to its high optical depth (0.4–2.5), are confined between Cordelia's and Ophelia's orbits. Portia and Rosalind are shepherd moons of the 3.800 km-wide *v* ring while Mab orbits within the 17.000 km-wide μ ring.

Neptune is circled by an obscure ring system made up of five principal structures (Table 4). Adams (outer ring, Fig. 6, *right panel*) shows three bright arcs and a clumpy azimuthal structure probably caused by nearby Larissa and Galatea moons; Lassell is a 4000 km-wide diffuse ring made of micron-sized dust particles. Galle, the inner ring, is a diffuse ring extending up to the top of Neptune clouds.

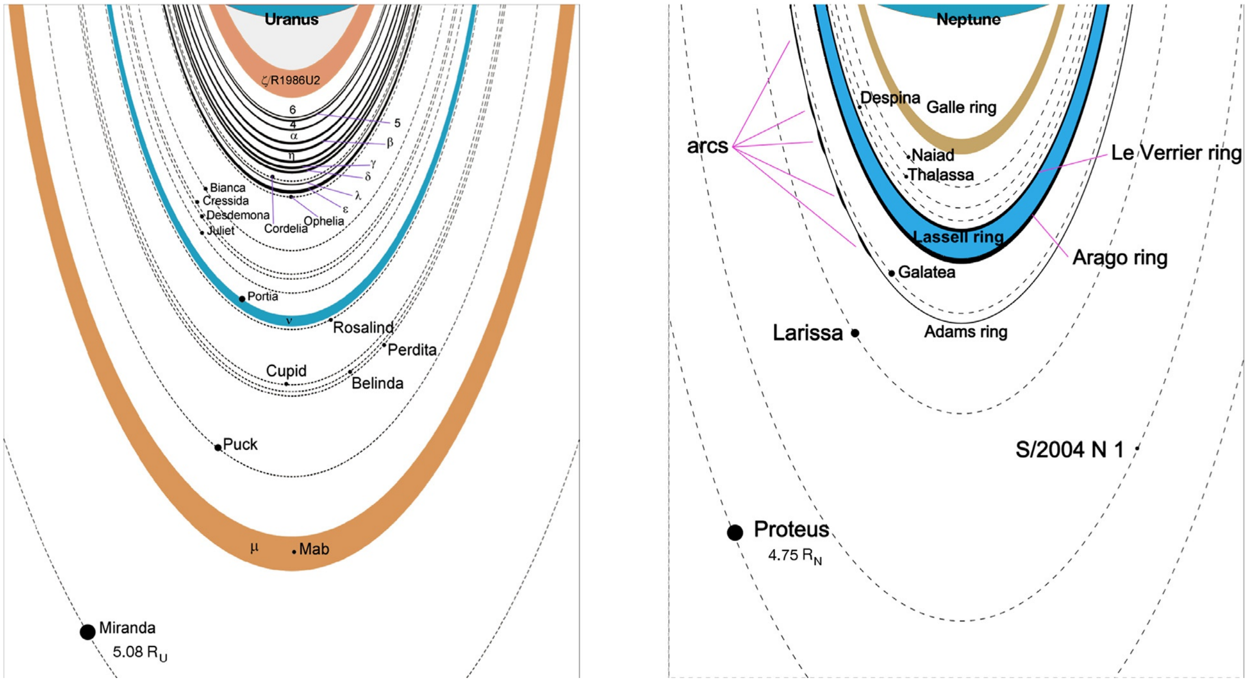

Fig. 6 Uranus (*left panel*) and Neptune (*right panel*) ring systems and nearby moons. Public domain image.

Table 4 Neptune rings properties.

Ring	*Radius (km)*	*Width (km)*	*Optical depth*
Galle	40,900–42,900	2000	≈0.0001
Le Verrier	53,180–53,220	113	0.0062
Lassell	53,200–57,200	4000	≈0.0001
Arago	57,200	<100	Unknown
Adams	62,930–62,934	15–50	0.011 (0.03–0.09 in arcs)

Apart observations carried out by the Voyager 2 mission, Uranus and Neptune satellite and ring systems are still largely unexplored because are very faint objects to be observed and studied from Earth. Until a new exploration mission will be selected and realized, our knowledge of these planetary systems will remain very limited.

Further Reading

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