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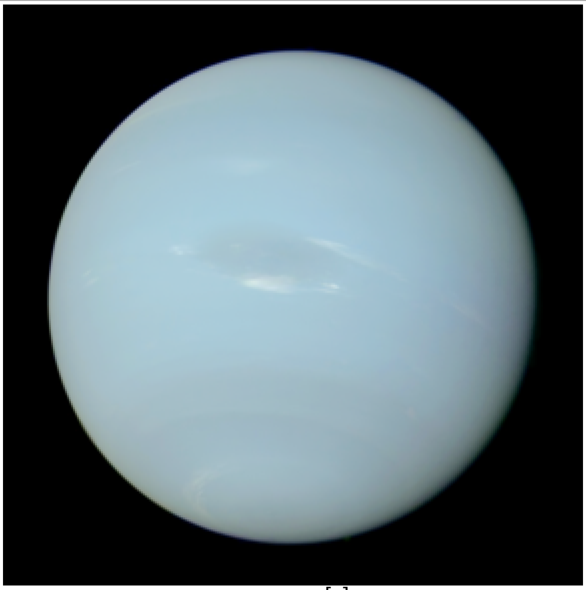
Neptune

Neptune is the eighth and farthest known planet from the Sun. It is the fourth-largest planet in the Solar System by diameter, the third-most-massive planet, and the densest giant planet. It is 17 times the mass of Earth, and slightly more massive than fellow ice giant Uranus. Neptune is denser and physically smaller than Uranus because its greater mass causes more gravitational compression of its atmosphere. Being composed primarily of gases and liquids, it has no well-defined solid surface. The planet orbits the Sun once every 164.8 years at an orbital distance of 30.1 astronomical units (4.5 billion kilometres; 2.8 billion miles). It is named after the Roman god of the sea and has the astronomical symbol ♆, representing Neptune's trident.[f]

Neptune is not visible to the unaided eye and is the only planet in the Solar System that was found from mathematical predictions derived from indirect observations rather than being initially observed by direct empirical observation. Unexpected changes in the orbit of Uranus led Alexis Bouvard to hypothesise that its orbit was subject to gravitational perturbation by an unknown planet. After Bouvard's death, the position of Neptune was predicted from his observations, independently, by John Couch Adams and Urbain Le Verrier. Neptune was subsequently directly observed with a telescope on 23 September 1846[1] by Johann Gottfried Galle within a degree of the position predicted by Le Verrier. Its largest moon, Triton, was discovered shortly thereafter, though none of the planet's remaining 15 known moons were located telescopically until the 20th century. The planet's distance from Earth gives it a small apparent size, making it challenging to study with Earth-based telescopes. Neptune was visited by *Voyager 2*, when it flew by the planet on 25 August 1989; *Voyager 2* remains the only spacecraft to have visited it.[18][19] The advent of the Hubble Space Telescope and large ground-based telescopes with adaptive optics has allowed for additional detailed observations from afar.

Neptune



Neptune in true colour[a] as captured by *Voyager 2*. Like Uranus, Neptune has a muted appearance; several storms can still be seen, such as Great Dark Spot GDS-89[b] at the center

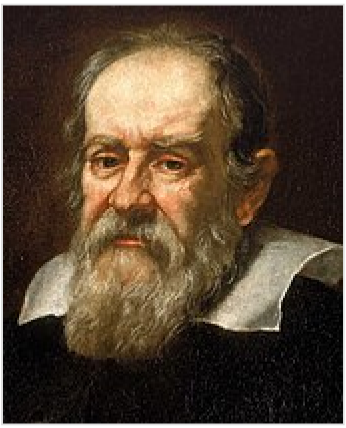
Discovery[1]	
Discovered by	Johann Galle Urbain Le Verrier John Couch Adams
Discovery date	23 September 1846
Designations	
Pronunciation	US: /ˈnɛptuːn/ ⓘ, UK: /-tjuːn/[2]
Named after	Latin *Neptunus*, via French *Neptune*
Adjectives	Neptunian (/nɛpˈtjuːniən/),[3] Poseidean[4]
Symbol	♆, historically also ⯉
Orbital characteristics[5][c]	
Epoch J2000	
Aphelion	30.33 AU (4.54 billion km)

Like the gas giants (Jupiter and Saturn), Neptune's atmosphere is composed primarily of hydrogen and helium, along with traces of hydrocarbons and possibly nitrogen, but contains a higher proportion of *ices* such as water, ammonia and methane. Similar to Uranus, its interior is primarily composed of ices and rock;[20] both planets are normally considered "ice giants" to distinguish them.[21] Along with Rayleigh scattering, traces of methane in the outermost regions make Neptune appear faintly blue.[22][23]

In contrast to the strongly seasonal atmosphere of Uranus, which can be featureless for long periods of time, Neptune's atmosphere has active and consistently visible weather patterns. At the time of the *Voyager 2* flyby in 1989, the planet's southern hemisphere had a Great Dark Spot comparable to the Great Red Spot on Jupiter. In 2018, a newer main dark spot and smaller dark spot were identified and studied.[24] These weather patterns are driven by the strongest sustained winds of any planet in the Solar System, as high as 2,100 km/h (580 m/s; 1,300 mph).[25] Because of its great distance from the Sun, Neptune's outer atmosphere is one of the coldest places in the Solar System, with temperatures at its cloud tops approaching 55 K (−218 °C; −361 °F). Temperatures at the planet's centre are approximately 5,400 K (5,100 °C; 9,300 °F).[26][27] Neptune has a faint and fragmented ring system (labelled "arcs"), discovered in 1984 and confirmed by *Voyager 2*.[28]

History

Discovery

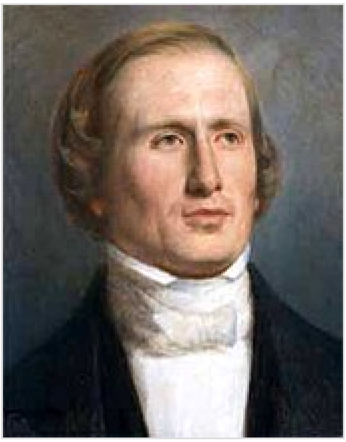

Galileo Galilei

Some of the earliest recorded observations ever made through a telescope, Galileo Galilei's drawings on 28 December 1612 and 27 January 1613 contain plotted points that match with what is now known to have been the positions of Neptune on those dates. On both

Perihelion	29.81 AU (4.46 billion km)
Semi-major axis	30.07 AU (4.50 billion km)
Eccentricity	0.008 678
Orbital period (sidereal)	164.8 yr 60,195 days 89,666 Neptunian solar days[6]
Orbital period (synodic)	367.49 days[7]
Average orbital speed	5.43 km/s[7]
Mean anomaly	259.883°
Inclination	1.770° to ecliptic 6.43° to Sun's equator 0.74° to invariable plane[8]
Longitude of ascending node	131.783°
Time of perihelion	2042-Sep-04[9]
Argument of perihelion	273.187°
Known satellites	16
Physical characteristics	
Mean radius	24,622 ± 19 km[10][d]
Equatorial radius	24,764 ± 15 km[10][d] 3.883 Earths
Polar radius	24,341 ± 30 km[10][d] 3.829 Earths
Flattening	0.0171 ± 0.0013
Surface area	7.6187×10^9 km^2[11][d] 14.98 Earths
Volume	6.253×10^{13} km^3[7][d] 57.74 Earths
Mass	$1.024\,09 \times 10^{26}$ kg[7] 17.147 Earths 5.15×10^{-5} Suns
Mean density	1.638 g/cm^3[7][e]
Surface gravity	11.15 m/s^2[7][d] 1.14 *g*
Moment of inertia factor	0.23[12] (estimate)

occasions, Galileo seems to have mistaken Neptune for a fixed star when it appeared close—in conjunction—to Jupiter in the night sky.[29] Hence, he is not credited with Neptune's discovery. At his first observation in December 1612, Neptune was almost stationary in the sky because it had just turned retrograde that day. This apparent backward motion is created when Earth's orbit takes it past an outer planet. Because Neptune was only beginning its yearly retrograde cycle, the motion of the planet was far too slight to be detected with Galileo's small telescope.[30] In 2009, a study suggested that Galileo was at least aware that the "star" he had observed had moved relative to fixed stars.[31]

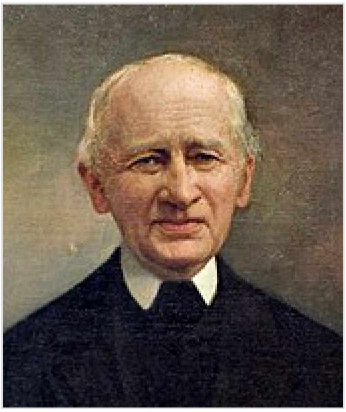
In 1821, Alexis Bouvard published astronomical tables of the orbit of Neptune's neighbour Uranus.[32] Subsequent observations revealed substantial deviations from the tables, leading Bouvard to hypothesise that an unknown body was perturbing the orbit through gravitational interaction.[33] In 1843, John Couch Adams began work on the orbit of Uranus using the data he had. He requested extra data from Sir George Airy, the Astronomer Royal, who supplied it in February 1844. Adams continued to work in 1845–1846 and produced several different estimates of a new planet.[34][35]



Urbain Le Verrier, the French astronomer who mostly successfully predicted Neptune's position in the sky using pure mathematics

In 1845–1846, Urbain Le Verrier, developed his own calculations independently from Adams, but aroused no enthusiasm among his compatriots. In June 1846, upon seeing Le Verrier's first published estimate of the planet's longitude and its similarity to Adams's estimate, Airy persuaded James Challis to search for the planet. Challis vainly scoured the sky throughout August and September.[33][36] Challis had, in fact, observed Neptune a year before the planet's subsequent discoverer, Johann Gottfried Galle, and on two occasions, 4 and 12 August 1845. However, his out-of-date star maps and poor observing techniques meant that he failed to recognise the observations as such until he carried out later analysis. Challis was full of remorse but blamed his neglect on his maps and the fact that he was distracted by his concurrent work on comet observations.[37][33][38]

Escape velocity	23.5 km/s[7][d]
Synodic rotation period	0.671 25 d 16 h 6 m 36 s[6]
Sidereal rotation period	0.6713 day[7] 16 h 6 min 36 s
Equatorial rotation velocity	2.68 km/s (9,650 km/h)
Axial tilt	28.32° (to orbit)[7]
North pole right ascension	$19^h\ 57^m\ 20^s$[10] 299.3°
North pole declination	42.950°[10]
Albedo	0.290 (bond)[13] 0.442 (geom.)[14]
Surface temp.	**min** **mean** **max**
1 bar level	72 K (−201 °C)[7]
0.1 bar (10 kPa)	55 K (−218 °C)[7]
Apparent magnitude	7.67[15] to 8.00[15]
Absolute magnitude *(H)*	−6.9[16]
Angular diameter	2.2–2.4″[7][17]
Atmosphere[7]	
Scale height	19.7 ± 0.6 km
Composition by volume	80% ± 3.2% hydrogen 19% ± 3.2% helium 1.5% ± 0.5% methane ~0.019% hydrogen deuteride ~0.00015% ethane Icy volatiles: ammonia, water ice, ammonium hydrosulfide, methane ice (?)



Johann Galle who was requested by Le Verrier to look for Neptune using the Berlin Observatory's telescope

Meanwhile, Le Verrier sent a letter and urged Berlin Observatory astronomer Galle to search with the observatory's refractor. Heinrich d'Arrest, a student at the observatory, suggested to Galle that they could compare a recently drawn chart of the sky in the region of Le Verrier's predicted location with the current sky to seek the displacement characteristic of a planet, as opposed to a fixed star. On the evening of 23 September 1846, the day Galle received the letter, he discovered Neptune just northeast of Iota Aquarii, 1° from the "*five degrees east of Delta Capricorn*" position Le Verrier had predicted it to be,[39][40] about 12° from Adams's prediction, and on the border of Aquarius and Capricornus according to the modern IAU constellation boundaries.

John Couch Adams the British astronomer who independently calculated Neptune's position

In the wake of the discovery, there was a heated nationalistic rivalry between the French and the British over who deserved credit for the discovery. Eventually, an international consensus emerged that Le Verrier and Adams deserved joint credit. Since 1966, Dennis Rawlins has questioned the credibility of Adams's claim to co-discovery, and the issue was re-evaluated by historians with the return in 1998 of the "Neptune papers" (historical documents) to the Royal Observatory, Greenwich.[41][42]

The 9" refractor used by Galle to discover Neptune

Naming

Shortly after its discovery, Neptune was referred to simply as "the planet exterior to Uranus" or as "Le Verrier's planet". The first suggestion for a name came from Galle, who proposed the name *Janus*. In England, Challis put forward the name *Oceanus*.[43]

Claiming the right to name his discovery, Le Verrier quickly proposed the name *Neptune* for this new planet, though falsely stating that this had been officially approved by the French Bureau des Longitudes.[44] In October, he sought to name the planet *Le Verrier*, after himself, and he had loyal support in this from the observatory director, François Arago. This suggestion met with stiff resistance outside France.[45] French almanacs quickly reintroduced the name *Herschel* for Uranus, after that planet's discoverer Sir William Herschel, and *Leverrier* for the new planet.[46]

Struve came out in favour of the name *Neptune* on 29 December 1846, to the Saint Petersburg Academy of Sciences,[47] after the colour of the planet as viewed through a telescope.[48] Soon, *Neptune* became the internationally accepted name. In Roman mythology, Neptune was the god of the sea, identified with the Greek Poseidon. The demand for a mythological name seemed to be in keeping with the nomenclature of the other planets, all of which were named for deities in Greek and Roman mythology.[g][49]

Most languages today use some variant of the name "Neptune" for the planet; indeed, in Chinese, Vietnamese, Japanese, and Korean, the planet's name was translated as "sea king star" (海王星).[50][51] In Mongolian, Neptune is called *Dalain van* (Далайн ван), reflecting its namesake god's role as the ruler of the sea. In modern Greek the planet is called *Poseidon* (Ποσειδώνας, *Poseidonas*), the Greek counterpart of Neptune.[52] In Hebrew, *Rahab* (רהב), from a Biblical sea monster mentioned in the Book of Psalms, was selected in a vote managed by the Academy of the Hebrew Language in 2009 as the official name for the planet, even though the existing Latin term *Neptun* (נפטון) is commonly used.[53][54] In Māori, the planet is called *Tangaroa*, named after the Māori god of the sea.[55] In Nahuatl, the planet is called *Tlāloccītlalli*, named after the rain god Tlāloc.[55] In Thai, Neptune is referred to by its Westernised name *Dao Nepchun/Nepjun* (ดาวเนปจูน), but is also called *Dao Ket* (ดาวเกตุ, lit. 'star of Ketu'), after Ketu (केतु), the descending lunar node, who plays a role in Hindu astrology. In Malay, the name *Waruna*, after the Hindu god of seas, is attested as far back as the 1970s,[56] but was eventually superseded by the Latinate equivalents *Neptun* (in Malaysian[57]) or *Neptunus* (in Indonesian[58]).

The usual adjectival form is *Neptunian*. The nonce form *Poseidean* (/pəˈsaɪdiən/), from Poseidon, has also been used,[4] though the usual adjectival form of Poseidon is *Poseidonian* (/ˌpɒsaɪˈdoʊniən/).[59]

Status

From its discovery in 1846 until the discovery of Pluto in 1930, Neptune was the farthest known planet. When Pluto was discovered, it was considered a planet, and Neptune thus became the second-farthest known planet, except for a 20-year period between 1979 and 1999 when Pluto's elliptical orbit brought it closer than Neptune to the Sun, making Neptune the ninth planet from the Sun during this period.[60][61] The increasingly accurate estimations of Pluto's mass from ten times that of Earth's to far less than that of the Moon[62] and the discovery of the Kuiper belt in 1992 led many astronomers to debate whether Pluto should be considered a planet or as part of the Kuiper belt.[63][64] In 2006, the International Astronomical Union defined the word "planet" for the first time, reclassifying Pluto as a "dwarf planet" and making Neptune once again the outermost-known planet in the Solar System.[65]

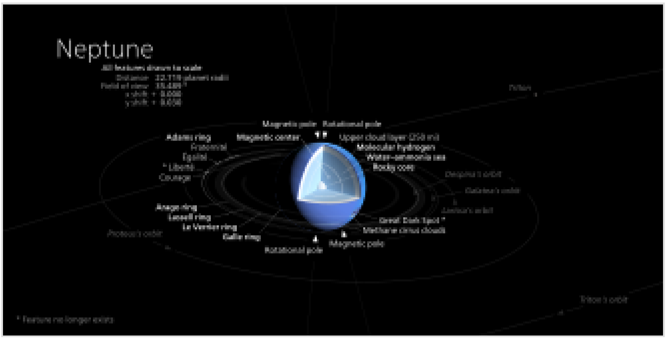
Physical characteristics

Neptune's mass of 1.0243×10^{26} kg[7] is intermediate between Earth and the larger gas giants: it is 17 times that of Earth but just 1/19th that of Jupiter.[h] Its gravity at 1 bar is 11.15 m/s^2, 1.14 times the surface gravity of Earth,[66] and surpassed only by Jupiter.[67] Neptune's equatorial radius of 24,764 km[10] is nearly four times that of Earth. Neptune, like Uranus, is an ice giant, a subclass of giant planet, because they are smaller and have higher concentrations of volatiles than Jupiter and Saturn.[68] In the search for exoplanets, Neptune has been used as a metonym: discovered bodies of similar mass are often referred to as "Neptunes",[69] just as scientists refer to various extrasolar bodies as "Jupiters".

A size comparison of Neptune and Earth

Internal structure

Neptune's internal structure resembles that of Uranus. Its atmosphere forms about 5 to 10% of its mass and extends perhaps 10 to 20% of the way towards the core. Pressure in the atmosphere reaches about 10 GPa, or about 100,000 times that of Earth's atmosphere. Increasing concentrations of methane, ammonia and water are found in the lower regions of the atmosphere.[26]



Physical and chemical composition of Neptune's interior

The mantle is equivalent to 10 to 15 Earth masses and is rich in water, ammonia and methane.[1] As is customary in planetary science, this mixture is referred to as icy even though it is a hot, dense fluid (supercritical fluid). This fluid, which has a high electrical conductivity, is sometimes called a water–ammonia ocean.[70] The mantle may consist of a layer of ionic water in which the water molecules break down into a soup of hydrogen and oxygen ions, and deeper down superionic water in which the oxygen crystallises but the hydrogen ions float around freely within the oxygen lattice.[71] At a depth of 7,000 km, the conditions may be such that methane decomposes into diamond crystals that rain downwards like hailstones.[72][73][74] Scientists also believe that this kind of diamond rain occurs on Jupiter, Saturn, and Uranus.[75][73] Very-high-pressure experiments at the Lawrence Livermore National Laboratory suggest that the top of the mantle may be an ocean of liquid carbon with floating solid 'diamonds'.[76][77][78]

The core of Neptune is likely composed of iron, nickel and silicates, with an interior model giving a mass about 1.2 times that of Earth.[79] The pressure at the centre is 7 Mbar (700 GPa), about twice as high as that at the centre of Earth, and the temperature may be 5,400 K.[26][27]

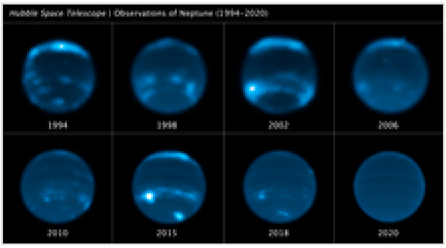
Atmosphere


Combined colour and near-infrared image of Neptune, showing bands of methane in its atmosphere, and four of its moons, Proteus, Larissa, Galatea, and Despina

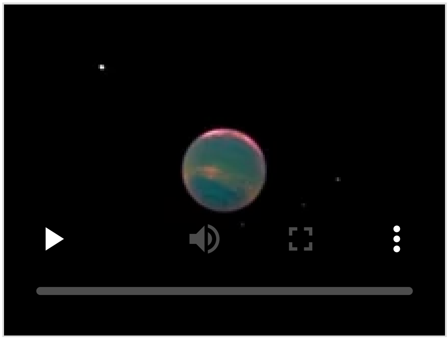
At high altitudes, Neptune's atmosphere is 80% hydrogen and 19% helium.[26] A trace amount of methane is also present. Prominent absorption bands of methane exist at wavelengths above 600 nm, in the red and infrared portion of the spectrum. As with Uranus, this absorption of red light by atmospheric methane is part of what gives Neptune its faint blue hue,[80] which is more pronounced for Neptune's due to concentrated haze in Uranus's atmosphere.[81][82]

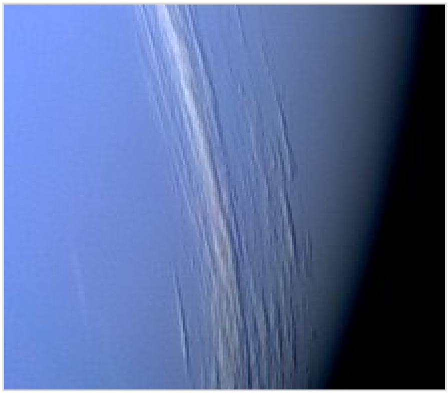
Neptune's atmosphere is subdivided into two main regions: the lower troposphere, where temperature decreases with altitude, and the stratosphere, where temperature increases with altitude. The boundary between the two, the tropopause, lies at a pressure of 0.1 bars (10 kPa).[21] The stratosphere then gives way to the thermosphere at a pressure lower than 10^{-5} to 10^{-4} bars (1 to 10 Pa).[21] The thermosphere gradually transitions to the exosphere.

Models suggest that Neptune's troposphere is banded by clouds of varying compositions depending on altitude.[83] The upper-level clouds lie at pressures below one bar, where the temperature is suitable for methane to condense. For pressures between one and five bars (100 and 500 kPa), clouds of ammonia and hydrogen sulfide are thought to form. Above a pressure of five bars, the clouds may consist of ammonia, ammonium sulfide, hydrogen sulfide and water. Deeper clouds of water ice should be found at pressures of about 50 bars (5.0 MPa), where the temperature reaches 273 K (0 °C). Underneath, clouds of ammonia and hydrogen sulfide may be found.[84]



Neptune – cloud cover over three decades (1994-2023)[83] False colour image based on data from WFPC2 and WFC3 instruments of the Hubble Space Telescope.


A time-lapse video of Neptune and its moons


Bands of high-altitude clouds cast shadows on Neptune's lower cloud deck. The colour is exaggerated to show the clouds more clearly.

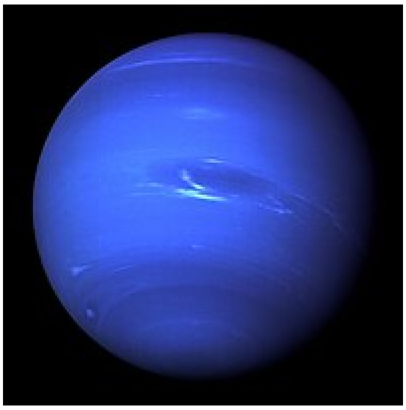
High-altitude clouds on Neptune have been observed casting shadows on the opaque cloud deck below. There are also high-altitude cloud bands that wrap around the planet at constant latitudes. These circumferential bands have widths of 50–150 km and lie about 50–110 km above the cloud deck.[85] These altitudes are in the layer where weather occurs, the troposphere. Weather does not occur in the higher stratosphere or thermosphere. In August 2023, the clouds of Neptune vanished, possibly due to "solar flare".[83] Thirty years of observations by the Hubble Space Telescope and ground-based telescopes showed that Neptune's cloud activity is bound to Solar cycles, and not to the planet's seasons.[86][87]

Neptune's spectra suggest that its lower stratosphere is hazy due to condensation of products of ultraviolet photolysis of methane, such as ethane and ethyne.[21][26] The stratosphere is also home to trace amounts of carbon monoxide and hydrogen cyanide.[21][88] The stratosphere of Neptune is warmer than that of Uranus due to the elevated concentration of hydrocarbons.[21]

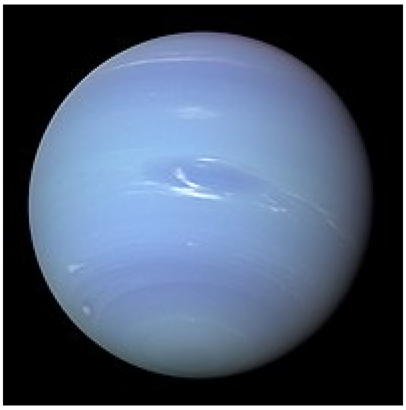
For reasons that remain obscure, the planet's thermosphere is at an anomalously high temperature of about 750 K.[89][90] The planet is too far from the Sun for this heat to be generated by ultraviolet radiation. One candidate for a heating mechanism is atmospheric interaction with ions in the planet's magnetic field. Other candidates are gravity waves from the interior that dissipate in the atmosphere. The thermosphere contains traces of carbon dioxide and water, which may have been deposited from external sources such as meteorites and dust.[84][88]

Colour

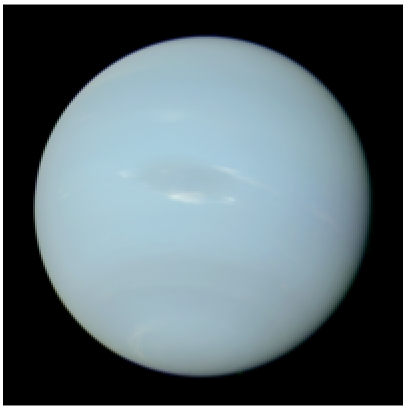
Neptune's atmosphere is faintly blue in the optical spectrum, only slightly more saturated than the blue of Uranus's atmosphere. Early renderings of the two planets greatly exaggerated Neptune's colour, making it seem deep blue to Uranus's off-white. The two planets had also been imaged with different systems, making it hard to directly compare the resulting composited images. This was revisited and the colour normalised over time, most comprehensively in late 2023.[82][91]



Original 2-colour (orange-green) NASA/JPL image from Voyager 2, with exaggerated colour.[92]



Colour recalibrated in 2016 (Justin Cowart), preserving some enhancement for contrast[93]



Colour recalibrated in 2023 (Patrick Irwin), approximating true colour[94]

Magnetosphere

Neptune resembles Uranus in its magnetosphere, with a magnetic field strongly tilted relative to its rotational axis at 47° and offset at least 0.55 radius, or about 13,500 km from the planet's physical centre. Before *Voyager 2*'s arrival at Neptune, it was hypothesised that Uranus's tilted magnetosphere was the result of its sideways rotation. In comparing the magnetic fields of the two planets, scientists now think the extreme orientation may be characteristic of flows in the planets' interiors. This field may be generated by convective fluid motions in a thin spherical shell of electrically conducting liquids (probably a combination of ammonia, methane and water)[84] resulting in a dynamo action.[95]

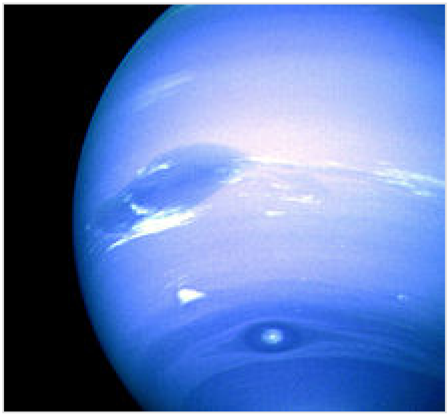
The dipole component of the magnetic field at the magnetic equator of Neptune is about 14 microteslas (0.14 G).[96] The dipole magnetic moment of Neptune is about 2.2×10^{17} T·m^3 (14 μT·$R_N{}^3$, where R_N is the radius of Neptune). Neptune's magnetic field has a complex geometry that includes relatively large contributions from non-dipolar components, including a strong quadrupole moment that may exceed the dipole moment in strength. By contrast, Earth, Jupiter and Saturn have only relatively small quadrupole moments, and their fields are less tilted from the polar axis. The large quadrupole moment of Neptune may be the result of an offset from the planet's centre and geometrical constraints of the field's dynamo generator.[97][98]

Measurements by *Voyager 2* in extreme-ultraviolet and radio frequencies revealed that Neptune has faint and weak but complex and unique aurorae; however, these observations were limited in time and did not contain infrared. Subsequent astronomers using the Hubble Space Telescope have not glimpsed the aurorae, in contrast to the more well-defined aurorae of Uranus.[99][100]

Neptune's bow shock, where the magnetosphere begins to slow the solar wind, occurs at a distance of 34.9 times the radius of the planet. The magnetopause, where the pressure of the magnetosphere counterbalances the solar wind, lies at a distance of 23–26.5 times the radius of Neptune. The tail of the magnetosphere extends out to at least 72 times the radius of Neptune, and likely much farther.[97]

Climate

Neptune's weather is characterised by extremely dynamic storm systems, with winds reaching speeds of almost 600 m/s (2,200 km/h; 1,300 mph)—exceeding supersonic flow.[25] More typically, by tracking the motion of persistent clouds, wind speeds have been shown to vary from 20 m/s in the easterly direction to 325 m/s westward.[102] At the cloud tops, the prevailing winds range in speed from 400 m/s along the equator to 250 m/s at the poles.[84] Most of the winds on Neptune move in a direction opposite the planet's rotation.[103] The general pattern of winds showed prograde rotation at high latitudes vs. retrograde rotation at lower latitudes. The difference in flow direction is thought to be a "skin effect" and not due to any deeper atmospheric processes.[21] At 70° S latitude, a high-speed jet travels at a speed of 300 m/s.[21]



The Great Dark Spot (top), Scooter (middle white cloud),[101] and the Small Dark Spot (bottom), with contrast exaggerated.

Neptune differs from Uranus in its typical level of meteorological activity. *Voyager 2* observed weather phenomena on Neptune during its 1989 flyby,[104] but no comparable phenomena on Uranus during its 1986 fly-by.

The abundance of methane, ethane and acetylene at Neptune's equator is 10–100 times greater than at the poles. This is interpreted as evidence for upwelling at the equator and subsidence near the poles, as photochemistry cannot account for the distribution without meridional circulation.[21]

In 2007, it was discovered that the upper troposphere of Neptune's south pole was about 10 K warmer than the rest of its atmosphere, which averages approximately 73 K (−200 °C). The temperature differential is enough to let methane, which elsewhere is frozen in the troposphere, escape into the stratosphere near the pole.[105] The relative "hot spot" is due to Neptune's axial tilt, which has exposed the south pole to the Sun for the last quarter of Neptune's year, or roughly 40 Earth years. As Neptune slowly moves towards the opposite side of the Sun, the south pole will be darkened and the north pole illuminated, causing the methane release to shift to the north pole.[106]

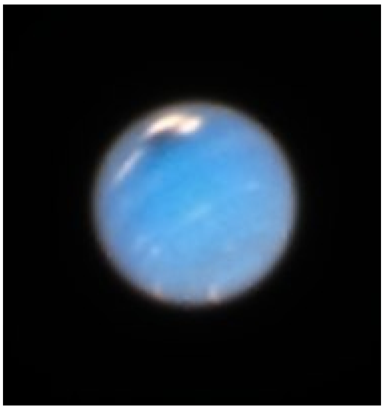
Because of seasonal changes, the cloud bands in the southern hemisphere of Neptune have been observed to increase in size and albedo. This trend was first seen in 1980. The long orbital period of Neptune results in seasons lasting forty years.[107]

Storms

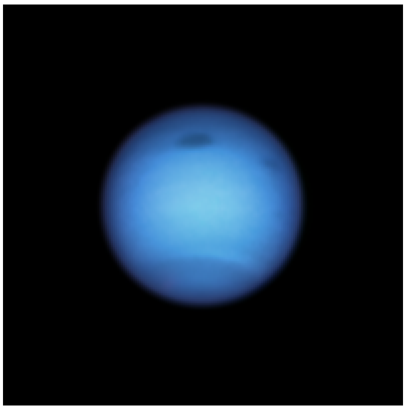
In 1989, the Great Dark Spot, an anticyclonic storm system spanning 13,000 km × 6,600 km (8,100 mi × 4,100 mi)[104] was discovered by NASA's *Voyager 2* spacecraft. The storm resembled the Great Red Spot of Jupiter. Some five years later, on 2 November 1994, the Hubble Space Telescope did not see the Great Dark Spot on the planet. Instead, a new storm similar to the Great Dark Spot was found in Neptune's northern hemisphere.[108]

The Scooter is another storm, a white cloud group farther south than the Great Dark Spot. This nickname first arose during the months leading up to the *Voyager 2* encounter in 1989, when they were observed moving at speeds faster than the Great Dark Spot (and images acquired later would subsequently reveal the presence of clouds moving even faster than those that had initially been detected by *Voyager 2*).[103] The Small Dark Spot is a southern cyclonic storm, the second-most-intense storm observed during the 1989 encounter. It was initially completely dark, but as *Voyager 2* approached the planet, a bright core developed, which can be seen in most of the highest-resolution images.[109] In 2018, a newer main dark spot and smaller dark spot were identified and studied.[24] In 2023, the first ground-based observation of a dark spot on Neptune was announced.[110]

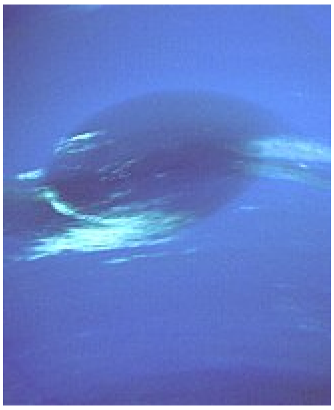
Neptune's dark spots are thought to occur in the troposphere at lower altitudes than the brighter cloud features,[111] so they appear as holes in the upper cloud decks. As they are stable features that can persist for several months, they are thought to be vortex structures.[85] Often associated with dark spots are brighter, persistent methane clouds that form around the tropopause layer.[112] The persistence of companion clouds shows that some former dark spots may continue to exist as cyclones even though they are no longer visible as a dark feature. Dark spots may dissipate when they migrate too close to the equator or possibly through some other, unknown mechanism.[113]



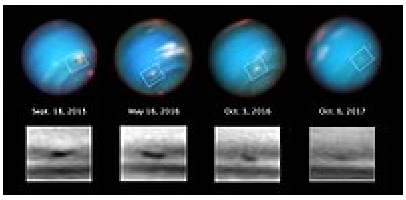
The appearance of a Northern Great Dark Spot in 2018 is evidence of a huge storm brewing.[114]



The Northern Great Dark Spot and a smaller companion storm imaged by Hubble in 2020[115]



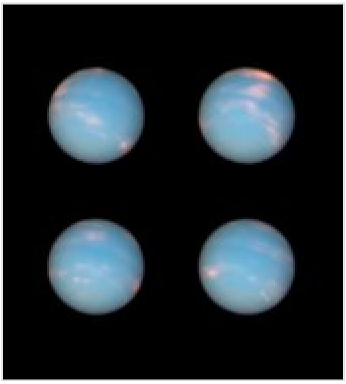
The Great Dark Spot in an enhanced colour image by *Voyager 2.*



Neptune's shrinking vortex[116]

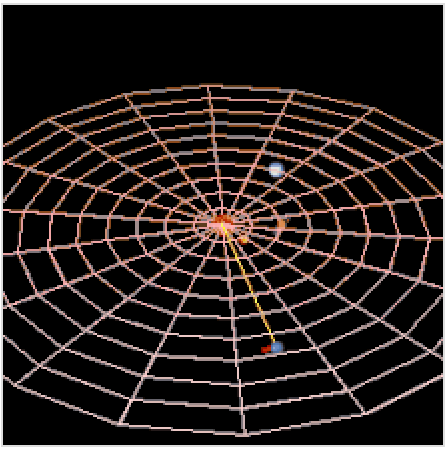
Internal heating

Neptune's more varied weather when compared to Uranus is due in part to its higher internal heating. The upper regions of Neptune's troposphere reach a low temperature of 51.8 K (−221.3 °C). At a depth where the atmospheric pressure equals 1 bar (100 kPa), the temperature is 72.00 K (−201.15 °C).[118] Deeper inside the layers of gas, the temperature rises steadily. As with Uranus, the source of this heating is unknown, but the discrepancy is larger: Uranus only radiates 1.1 times as much energy as it receives from the Sun;[119] whereas Neptune radiates about 2.61 times as much energy as it receives from the Sun.[120] Neptune is the farthest planet from the Sun, and lies over 50% farther from the Sun than Uranus, and receives only 40% of its amount of sunlight,[21] yet its internal energy is sufficient to drive the fastest planetary winds seen in the Solar System. Depending on the thermal properties of its interior, the heat left over from Neptune's formation may be sufficient to explain its current heat flow, though it is more difficult to simultaneously explain Uranus's lack of internal heat while preserving the apparent similarity between the two planets.[121]



Four images taken a few hours apart with the NASA/ESA *Hubble Space Telescope*'s Wide Field Camera 3. Near infrared radiation data has been used as red channel.[117]

Orbit and rotation



Neptune (red arc) completes one orbit around the Sun (centre) for every 164.79 orbits of Earth. The light blue object represents Uranus.

The average distance between Neptune and the Sun is 4.5 billion km (about 30.1 astronomical units (AU)), and it completes an orbit on average every 164.79 years, subject to a variability of around ±0.1 years. The perihelion distance is 29.81 AU; the aphelion distance is 30.33 AU.[i]

On 11 July 2011, Neptune completed its first full barycentric orbit since its discovery in 1846,[123] although it did not appear at its exact discovery position in the sky, because Earth was in a different location in its 365.26 day orbit. Because of the motion of the Sun in relation to the barycentre of the Solar System, on 11 July Neptune was also not at its exact discovery position in relation to the Sun; if the more common heliocentric coordinate system is used, the discovery longitude was reached on 12 July 2011.[11][124][125][126]

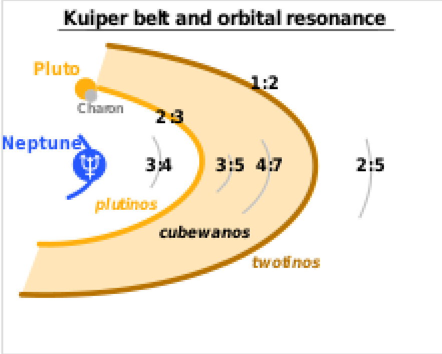
Neptune's orbital eccentricity is only at 0.008678. This makes it the planet in the Solar System with the second most circular orbit after Venus.[127] The orbit of Neptune is inclined 1.77° compared to that of Earth.

The axial tilt of Neptune is 28.32°,[128] which is similar to the tilts of Earth (23°) and Mars (25°). As a result, Neptune experiences seasonal changes similar to those on Earth. The long orbital period of Neptune means that the seasons last for forty Earth years.[107] Its sidereal rotation period (day) is roughly 16.11 hours.[11] Because its axial tilt is comparable to Earth's, the variation in the length of its day over the course of its long year is not any more extreme.

Because Neptune is not a solid body, its atmosphere undergoes differential rotation. The wide equatorial zone rotates with a period of about 18 hours, which is slower than the 16.1-hour rotation of the planet's magnetic field. By contrast, the reverse is true for the polar regions where the rotation period is 12 hours. This differential rotation is the most pronounced of any planet in the Solar System,[129] and it results in strong latitudinal wind shear.[85]

Orbital resonances

Neptune's orbit has a profound impact on the region directly beyond it, known as the Kuiper belt. The Kuiper belt is a ring of small icy worlds, similar to the asteroid belt but far larger, extending from Neptune's orbit at 30 AU out to about 55 AU from the Sun.[130] Much in the same way that Jupiter's gravity dominates the asteroid belt, shaping its structure, so Neptune's gravity dominates the Kuiper belt. Over the age of the Solar System, certain regions of the Kuiper belt became destabilised by Neptune's gravity, creating gaps in its structure. The region between 40 and 42 AU is an example.[131]



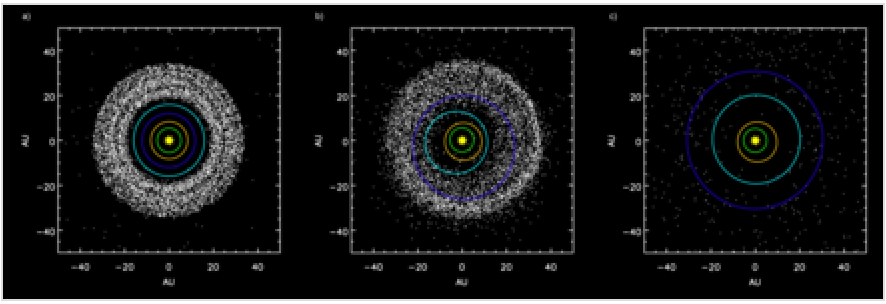
A diagram showing the major orbital resonances in the Kuiper belt caused by Neptune: the highlighted regions are the 2:3 resonance (plutinos), the nonresonant "classical belt" (cubewanos), and the 1:2 resonance (twotinos).

There do exist orbits within these empty regions where objects can survive for the age of the Solar System. These resonances occur when Neptune's orbital period is a precise fraction of that of the object, such as 1:2, or 3:4. If, say, an object orbits the Sun once for every two Neptune orbits, it will only complete half an orbit by the time Neptune returns to its original position. The most heavily populated resonance in the Kuiper belt, with over 200 known objects,[132] is the 2:3 resonance. Objects in this resonance complete 2 orbits for every 3 of Neptune, and are known as plutinos because the largest of the known Kuiper belt objects, Pluto, is among them.[133] Although Pluto crosses Neptune's orbit regularly, the 2:3 resonance ensures they can never collide.[134] The 3:4, 3:5, 4:7 and 2:5 resonances are less populated.[135]

Neptune has a number of known trojan objects occupying both the Sun–Neptune L_4 and L_5 Lagrangian points—gravitationally stable regions leading and trailing Neptune in its orbit, respectively.[136] Neptune trojans can be viewed as being in a 1:1 resonance with Neptune. Some Neptune trojans are remarkably stable in their orbits, and are likely to have formed alongside Neptune rather than being captured. The first object identified as associated with Neptune's trailing L_5 Lagrangian point was 2008 LC_{18}.[137] Neptune also has a temporary quasi-satellite, (309239) 2007 RW_{10}.[138] The object has been a quasi-satellite of Neptune for about 12,500 years and it will remain in that dynamical state for another 12,500 years.[138]

Formation and migration

The formation of the ice giants, Neptune and Uranus, has proven difficult to model precisely. Current models suggest that the matter density in the outer regions of the Solar System was too low to account for the formation of such large bodies from the traditionally accepted method of core accretion, and various hypotheses have been advanced to explain their

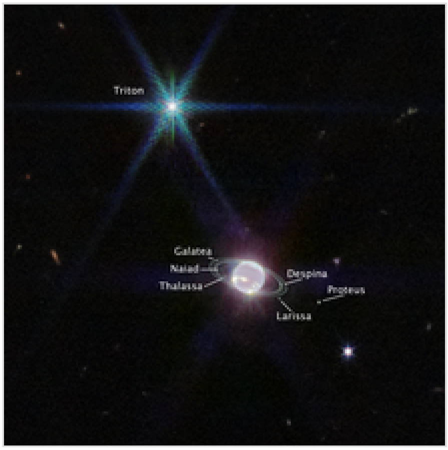

A simulation showing the outer planets and Kuiper belt: a) before Jupiter and Saturn reached a 2:1 resonance; b) after inward scattering of Kuiper belt objects following the orbital shift of Neptune; c) after ejection of scattered Kuiper belt bodies by Jupiter

formation. One is that the ice giants were not formed by core accretion but from instabilities within the original protoplanetary disc and later had their atmospheres blasted away by radiation from a nearby massive OB star.[68]

An alternative concept is that they formed closer to the Sun, where the matter density was higher, and then subsequently migrated to their current orbits after the removal of the gaseous protoplanetary disc.[139] This hypothesis of migration after formation is favoured, due to its ability to better explain the occupancy of the populations of small objects observed in the trans-Neptunian region.[140] The current most widely accepted[141][142][143] explanation of the details of this hypothesis is known as the Nice model, which explores the effect of a migrating Neptune and the other giant planets on the structure of the Kuiper belt.

Moons

Neptune has 16 known moons.[144] Triton is the largest Neptunian moon, accounting for more than 99.5% of the mass in orbit around Neptune,[j] and is the only one massive enough to be spheroidal. Triton was discovered by William Lassell just 17 days after the discovery of Neptune itself. Unlike all other large planetary moons in the Solar System, Triton has a retrograde orbit, indicating that it was captured rather than forming in place; it was probably once a dwarf planet in the Kuiper belt.[145] It is close enough to Neptune to be locked into a synchronous rotation, and it is slowly spiralling inward because of tidal acceleration. It will eventually be torn apart, in about 3.6 billion years, when it reaches the Roche limit.[146] In 1989, Triton was the coldest object that had yet been measured in the Solar System,[147] with estimated temperatures of 38 K (−235 °C).[148][149] This very low temperature is due to Triton's very high albedo which causes it to reflect a lot of sunlight instead of absorbing it.[150][151]



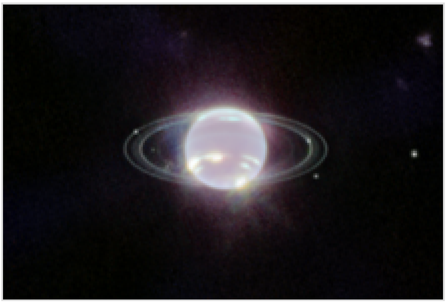
An annotated picture of Neptune's many moons as captured by the James Webb Space Telescope. The bright blue diffraction star is Triton, Neptune's largest moon.

Neptune's second-known satellite (by order of discovery), the irregular moon Nereid, has one of the most eccentric orbits of any satellite in the Solar System. The eccentricity of 0.7512 gives it an apoapsis that is seven times its periapsis distance from Neptune.[k]

From July to September 1989, *Voyager 2* discovered six moons of Neptune.[152] Of these, the irregularly shaped Proteus is notable for being as large as a body of its density can be without being pulled into a spherical shape by its own gravity.[153] Although the second-most-massive Neptunian moon, it is only 0.25% the mass of Triton. Neptune's innermost four moons—Naiad, Thalassa, Despina and Galatea—orbit close enough to be within Neptune's rings. The next-farthest out, Larissa, was originally discovered in 1981 when it had occulted a star. This occultation had been attributed to ring arcs, but when *Voyager 2* observed Neptune in 1989, Larissa was found to have caused it. Five new irregular moons discovered between 2002 and 2003 were announced in 2004.[154][155] A new moon and the smallest yet, Hippocamp, was found in 2013 by combining multiple Hubble images.[156] Because Neptune was the Roman god of the sea, Neptune's moons have been named after lesser sea gods.[49]

Planetary rings

Neptune has a planetary ring system, though one much less substantial than that of Saturn.[157] The rings may consist of ice particles coated with silicates or carbon-based material, which most likely gives them a reddish hue.[158] The three main rings are the narrow Adams Ring, 63,000 km from the centre of Neptune, the Le Verrier Ring, at 53,000 km, and the broader, fainter Galle Ring, at 42,000 km. A faint outward extension to the Le Verrier Ring has been named Lassell; it is bounded at its outer edge by the Arago Ring at 57,000 km.[159]



Neptune's rings and moons viewed in infrared by the James Webb Space Telescope

The first of these planetary rings was detected in 1968 by a team led by Edward Guinan.[28][160] In the early 1980s, analysis of this data along with newer observations led to the hypothesis that this ring might be incomplete.[161] Evidence that the rings might have gaps first arose during a stellar occultation in 1984 when the rings obscured a star on immersion but not on emersion.[162] Images from *Voyager 2* in 1989 settled the issue by showing several faint rings.

The outermost ring, Adams, contains five prominent arcs now named *Courage*, *Liberté*, *Egalité 1*, *Egalité 2* and *Fraternité* (Courage, Liberty, Equality and Fraternity).[163] The existence of arcs was difficult to explain because the laws of motion would predict that arcs would spread out into a uniform ring over short timescales. Astronomers now estimate that the arcs are corralled into their current form by the gravitational effects of Galatea, a moon just inward from the ring.[164][165]

Earth-based observations announced in 2005 appeared to show that Neptune's rings were much more unstable than previously thought. Images taken from the W. M. Keck Observatory in 2002 and 2003 show considerable decay in the rings when compared to images by *Voyager 2*. In particular, it seems that the *Liberté* arc might disappear in as little as one century.[166]

Observation

Neptune brightened about 10% between 1980 and 2000 mostly due to the changing of the seasons.[167] Neptune may continue to brighten as it approaches perihelion in 2042. The apparent magnitude currently ranges from 7.67 to 7.89 with a mean of 7.78 and a standard deviation of 0.06.[15] Prior to 1980, the planet was as faint as magnitude 8.0.[15] Neptune is too faint to be visible to the naked eye. It can be outshone by Jupiter's Galilean moons, the dwarf planet Ceres and the asteroids 4 Vesta, 2 Pallas, 7 Iris, 3 Juno, and 6 Hebe.[168] A telescope or strong binoculars will resolve Neptune as a small blue disk, similar in appearance to Uranus.[169]

Because of the distance of Neptune from Earth, its angular diameter only ranges from 2.2 to 2.4 arcseconds,[7][17] the smallest of the Solar System planets. Its small apparent size makes it challenging to study visually. Most telescopic data was fairly limited until the advent of the Hubble Space Telescope and large ground-based telescopes with adaptive optics (AO).[170][171][172] The first scientifically useful observation of Neptune from ground-based telescopes using adaptive optics was commenced in 1997 from Hawaii.[173] Neptune is currently approaching perihelion (closest approach to the Sun) and has been shown to be heating up, with increased atmospheric activity and brightness as a consequence. Combined with technological advancements, ground-based telescopes with adaptive optics are recording increasingly more detailed images of it. Both *Hubble* and the adaptive-optics telescopes on Earth have made many new discoveries within the Solar System since the mid-1990s, with a large increase in the number of known satellites and moons around the outer planet, among others. In 2004 and 2005, five new small satellites of Neptune with diameters between 38 and 61 kilometres were discovered.[174]

Movement of Neptune in front of the stars of Aquarius in 2022

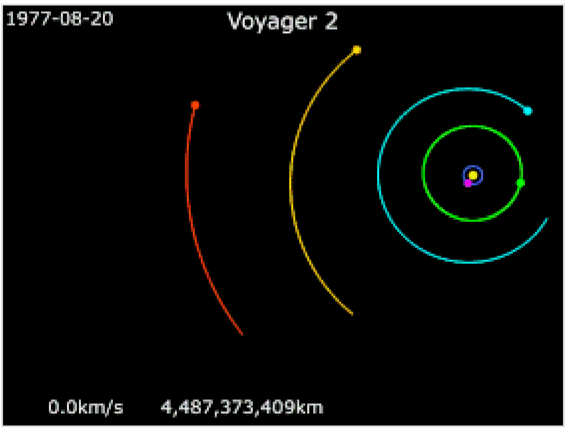
From Earth, Neptune goes through apparent retrograde motion every 367 days, resulting in a looping motion against the background stars during each opposition. These loops carried it close to the 1846 discovery coordinates in April and July 2010 and again in October and November 2011.[126]

Neptune's 164-year orbital period means that the planet takes an average of 13 years to move through each constellation of the zodiac. In 2011, it completed its first full orbit of the Sun since being discovered and returned to where it was first spotted northeast of Iota Aquarii.[39]

Observation of Neptune in the radio-frequency band shows that it is a source of both continuous emission and irregular bursts. Both sources are thought to originate from its rotating magnetic field.[84] In the infrared part of the spectrum, Neptune's storms appear bright against the cooler background, allowing the size and shape of these features to be readily tracked.[175]

Exploration

Voyager 2 is the only spacecraft that has visited Neptune. The spacecraft's closest approach to the planet occurred on 25 August 1989. Because this was the last major planet the spacecraft could visit, it was decided to make a close flyby of the moon Triton, regardless of the consequences to the trajectory, similarly to what was done for *Voyager 1*'s encounter with Saturn and its moon Titan. The images relayed back to Earth from *Voyager 2* became the basis of a 1989 PBS all-night program, *Neptune All Night*.[176]



Animation of *Voyager 2*'s trajectory from August 20, 1977, to December 30, 2000
Voyager 2 · Earth · Jupiter · Saturn · Uranus · Neptune · Sun

During the encounter, signals from the spacecraft required 246 minutes to reach Earth. Hence, for the most part, *Voyager 2*'s mission relied on preloaded commands for the Neptune encounter. The spacecraft performed a near-encounter with the moon Nereid before it came within 4,400 km of Neptune's atmosphere on 25 August, then passed close to the planet's largest moon Triton later the same day.[177]

The spacecraft verified the existence of a magnetic field surrounding the planet and discovered that the field was offset from the centre and tilted in a manner similar to the field around Uranus. Neptune's rotation period was determined using measurements of radio emissions and *Voyager 2* also showed that Neptune had a surprisingly active weather system. Six new moons were discovered, and the planet was shown to have more than one ring.[152][177]

The flyby also provided the first accurate measurement of Neptune's mass which was found to be 0.5 percent less than previously calculated. The new figure disproved the hypothesis that an undiscovered Planet X acted upon the orbits of Neptune and Uranus.[178][179]

Since 2018, the China National Space Administration has been studying a concept for a pair of *Voyager*-like interstellar probes tentatively known as *Shensuo*.[180] Both probes would be launched in the 2020s and take differing paths to explore opposing ends of the heliosphere; the second probe, *IHP-2*, would fly by Neptune in January 2038, passing only 1,000 km above the cloud tops, and potentially carry an atmospheric impactor to be released during its approach.[181] Afterward, it will continue on its mission throughout the Kuiper belt toward the tail of the heliosphere, so far unexplored.

After *Voyager 2* and *IHP-2*'s flybys, the next step in scientific exploration of the Neptunian system is considered to be an orbital mission; most proposals have been by NASA, most often for a Flagship orbiter.[182] Such a hypothetical mission is envisioned to be possible in the late 2020s or early 2030s.[182] However, there have been discussions to launch Neptune missions sooner. In 2003, there was a proposal in NASA's "Vision Missions Studies" for a "Neptune Orbiter with Probes" mission that does *Cassini*-level science.[183] A subsequent proposal was for *Argo*, a flyby spacecraft to be launched in 2019, that would visit Jupiter, Saturn, Neptune, and a Kuiper belt object. The focus would be on Neptune and its largest moon Triton to be investigated around 2029.[184] The proposed *New Horizons 2* mission (which was later scrapped) might also have done a close flyby of the Neptunian system. Currently a pending proposal for the Discovery program, *Trident* would conduct a flyby of Neptune and Triton;[185] however, the mission was not selected for Discovery 15 or 16. *Neptune Odyssey* is the current mission concept for a Neptune orbiter and atmospheric probe being studied as a possible large strategic science mission by NASA that would launch between 2031 and 2033, and arrive at Neptune by 2049.[186] Two notable proposals for a Triton-focused Neptune orbiter mission that would be costed right between the *Trident* and *Odyssey* missions (under the New Frontiers program) are *Triton Ocean Worlds Surveyor* and *Nautilus*, with cruise stages taking place in the 2031–47 and 2041-56 time periods, respectively.[187][188] Neptune is also a potential target for China's *Tianwen-5*, which could arrive in 2058.[189]

See also

- Outline of Neptune
- Hot Neptune
- Neptune in astrology
- Neptune in fiction
- Neptunium
- *Neptune, the Mystic* – one of the seven movements in Gustav Holst's *Planets* suite
- Timeline of the far future
- Stats of planets in the Solar System

Notes

a. Based on Irwin, Patrick G J; Dobinson, Jack; James, Arjuna; Teanby, Nicholas A; Simon, Amy A; Fletcher, Leigh N; Roman, Michael T; Orton, Glenn S; Wong, Michael H; Toledo, Daniel; Pérez-Hoyos, Santiago; Beck, Julie (23 December 2023). "Modelling the seasonal cycle of Uranus's colour and magnitude, and comparison with Neptune" (https://academic.oup.com/mnras/article/527/4/11521/7511973). *Monthly Notices of the Royal Astronomical Society*. **527** (4): 11521–11538. doi:10.1093/mnras/stad3761 (https://doi.org/10.1093%2Fmn ras%2Fstad3761). hdl:20.500.11850/657542 (https://hdl.handle.net/20.500.11850%2F657542). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711).

b. Neptune's dark spots are not permanent features; the large dark spot observed by *Voyager 2* was designated GDS-89 for "Great Dark Spot 1989"

c. Orbital elements refer to the Neptune barycentre and Solar System barycentre. These are the instantaneous osculating values at the precise J2000 epoch. Barycentre quantities are given because, in contrast to the planetary centre, they do not experience appreciable changes on a day-to-day basis from the motion of the moons.

d. Refers to the level of 1 bar (100 kPa) atmospheric pressure

e. Based on the volume within the level of 1 bar atmospheric pressure

f. A second symbol, an 'LV' monogram ⯉ for 'Le Verrier', analogous to the 'H' monogram ♅ for Uranus. It was never much used outside of France and is now archaic.

g. One might be tempted to say "except 'Earth'", which in the English language is the name of a Germanic deity, Erda. The IAU policy is that one may call the Earth and the Moon by any name commonly used in the language being used. Contrary to common use by science fiction writers, 'Terra' and 'Luna' are ***not*** the official names of planet Earth and its moon. *See* the wikipedia article Earth for references.

h. The mass of Earth is 5.9736×10^{24} kg, giving a mass ratio

$$\frac{M_{\text{Neptune}}}{M_{\text{Earth}}} = \frac{1.02 \times 10^{26}}{5.97 \times 10^{24}} = 17.09.$$

The mass of Uranus is 8.6810×10^{25} kg, giving a mass ratio

$$\frac{M_{\text{Uranus}}}{M_{\text{Earth}}} = \frac{8.68 \times 10^{25}}{5.97 \times 10^{24}} = 14.54.$$

The mass of Jupiter is 1.8986×10^{27} kg, giving a mass ratio

$$\frac{M_{\text{Jupiter}}}{M_{\text{Neptune}}} = \frac{1.90 \times 10^{27}}{1.02 \times 10^{26}} = 18.63.$$

Mass values from Williams, David R. (29 November 2007). "Planetary Fact Sheet – Metric" (http://nssdc.gsfc.nasa.gov/planetary/factsheet/). NASA. Archived (https://web.archive.org/web/20140905165712/http://nssdc.gsfc.nasa.gov/planetary/factsheet/) from the original on 5 September 2014. Retrieved 13 March 2008.

i. The last three aphelia were 30.33 AU, the next is 30.34 AU. The perihelia are even more stable at 29.81 AU.[122]

j. Mass of Triton: 2.14×10^{22} kg. Combined mass of 12 other known moons of Neptune: 7.53×10^{19} kg, or 0.35%. The mass of the rings is negligible.

k. $\frac{r_a}{r_p} = \frac{2}{1-e} - 1 = 2/0.2488 - 1 \approx 7.039.$

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External links

- NASA's Neptune fact sheet (http://nssdc.gsfc.nasa.gov/planetary/factsheet/neptunefact.html)
- Neptune (http://www.nineplanets.org/neptune.html) from Bill Arnett's nineplanets.org
- Neptune (http://www.astronomycast.com/astronomy/episode-63-neptune/) Astronomy Cast episode No. 63, includes full transcript.
- Neptune Profile (https://web.archive.org/web/20021115171710/http://solarsystem.nasa.gov/planets/profile.cfm?Object=Neptune) (archived 15 November 2002) at NASA's Solar System Exploration site (http://solarsystem.nasa.gov)
- Interactive 3D gravity simulation of Neptune and its inner moons (https://gravitysimulator.org/solar-system/the-neptunian-system) Archived (https://web.archive.org/web/20200922021820/https://gravitysimulator.org/solar-system/the-neptunian-system/) 22 September 2020 at the Wayback Machine