

GEOPHYSICAL, GRAVITATIONAL, AND MAGNETIC DATA ON NEPTUNE'S MOON TRITON

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Abstract. Neptune's largest satellite, Triton, moves in a retrograde orbit with an inclination of the orbital plane to the equator of Neptune close to 157° . Such parameters indicate that Triton is a captured object formed in the outer regions of the protoplanetary disk. Interaction with Neptune's gravitational field caused enormous tidal deformations in the satellite's body, which were accompanied by the release of a huge amount of heat. This tidal heating initiated a deep gravitational differentiation of matter into a metal core, a silicate mantle, and an ice shell. Analysis of the reflection spectra of the opposite hemispheres of Triton revealed a pronounced longitudinal asymmetry in the distribution of the most volatile substances. And less volatile compounds are thermodynamically stable at the average surface temperature of Triton ~ 38 K and are distributed extremely evenly over the surface and do not show significant long-term fluctuations. The relative contributions of carbon and nitrogen compounds in Triton's surface ices and atmosphere suggest a long-term influence of endogenous water processes. On Triton, much of the primary methane was chemically reprocessed by hydrothermal synthesis in the subsurface ocean. Thermal and geodynamic models suggest that after an era of extreme tidal heating, Triton's metallic Fe-FeS core could have retained enough heat to sustain convection to the present day. Voyager 2 data clearly indicate that Triton's surface is extremely young. The average age of surface structures is no more than 10–100 million years, and some regions of active cryovolcanism are even younger, less than 6–10 million years. Additional evidence for a long-term internal heat source comes from chemical tracers obtained from volatile compounds on Triton's surface. High-precision infrared spectroscopy confirmed the presence of a complex volatile and non-volatile cover, revealing anomalously deep carbon dioxide bands, signs of complex organic compounds, and atmospheric CO fluorescence. This indicates long-term endogenous and photochemical processes. The young surface age of Triton confirms its modern geological and cryovolcanic activity.

Keywords: Triton, tidal deformation, volatile and non-volatile substances, active cryovolcanism, young surface age.

Introduction. Neptune's largest moon, Triton, occupies a unique place among the bodies of the Solar System due to its anomalous physical and dynamic characteristics. It moves in a retrograde orbit in the direction opposite to the rotation of its host planet, with an inclination of the orbital plane to the equator of Neptune at an angle of close

to 157° . Such orbital parameters exclude the possibility of Triton's formation from the primary circumplanetary accretion disk of Neptune. It is generally accepted that Triton is a captured object formed in the outer regions of the protoplanetary disk as an independent dwarf planet of the Kuiper belt [18, 21], similar to Pluto or Eris, and was subsequently gravitationally captured by Neptune. The process of Triton's capture was catastrophic for the primary satellite system of Neptune. The gravity of the massive alien disrupted the orbits of the ice giant's regular moons, causing a series of mutual collisions and turning them into fragments, from which the modern generation of inner moons was later formed. Triton itself, after being captured, found itself in an extremely elongated, eccentric orbit with an eccentricity $e > 0.9$. The interaction with Neptune's powerful gravitational field caused colossal tidal deformations in the moon's body, which were accompanied by the release of a huge amount of heat. This tidal heating completely melted Triton's interior, initiating a deep gravitational differentiation of matter into a metallic core, a silicate mantle and an icy shell. The only spacecraft to study Triton up close is Voyager 2, which flew past the Neptune system in August 1989. Understanding the internal structure of Triton and the mechanisms that support its geological activity at such a significant distance from the Sun is a key task of modern planetary science and astrobiology [25], as this satellite is one of the most promising candidates for the status of a subsurface ocean world [5, 7, 14].

Spectroscopic discoveries with the James Webb Telescope. A new stage in the study of the physicochemical properties of Triton began thanks to observations using the James Webb Space Telescope (JWST). The observation program made it possible to obtain reflectance spectra of Triton in the near and mid-infrared ranges of unprecedented quality. Using near (NIRSpec) and mid-infrared (MIRI) spectrographs, high-precision spectral data were obtained on the surface composition of Triton, as well as the small inner satellites of Neptune (Proteus, Larissa, Galatea) and its ring system [21, 26].

JWST/NIRSpec observations have revealed a unique spectral feature on the surfaces of the small inner moons of Larissa and Galatea, and within the rings of Neptune, a band of absorption at $2.72 \mu\text{m}$. This band is a clear diagnostic marker for the presence of multibranched magnesium phyllosilicates (serpentine minerals such as antigorite, saponite, and talc). The presence of phyllosilicates is direct evidence of deep aqueous alteration of primary silicates upon interaction with liquid water at elevated temperatures ($T \sim 300 - 500 \text{ K}$). Since the small inner moons of Neptune are located in the middle of the Roche limit for water ice and have extremely low albedos ($< 10\%$), they could not have formed as primary cryogenic bodies. Modeling suggests that these inner moons and rings are the product of re-aggregation of debris generated during a catastrophic disruption of Neptune's primary moon system or during the destruction of the Triton precursor or its binary moon during gravitational capture. Thus, the materials of the inner Neptune moons act as a "petrological window" into the deep interior of differentiated icy bodies, confirming the existence of long-term hydrothermal processes in the interior of Triton itself.

The evolutionary path of the formation of the material of the inner Neptune system is traced from the primary binary Kuiper belt object or regular moon to the present state. When the Triton precursor entered Neptune's Hill sphere, the destruction of the companion moons occurred due to tidal disruption and collisions. The hydrothermally altered silicate cores of these bodies, containing phyllosilicates with a characteristic absorption at 2.72 μm , were crushed and thrown into periplanetary orbits. Subsequently, this deep material formed modern small satellites (Larissa, Galatea, Proteus) and formed the dust rings of Neptune.

Unlike previous ground-based observations, which were significantly limited by the absorption of the Earth's atmosphere [14], JWST instruments provided almost continuous spectral coverage in the range from 0.9 to 5.3 micrometers with a high resolution of $R \sim 2700$. To obtain and analyze the spectra of Triton, a modern technique of modeling the empirical point scattering function was used, which made it possible to separate the satellite's own radiation from the scattered light of Neptune and achieve a record signal-to-noise ratio. The obtained reflectance spectra revealed an extremely complex chemical structure of the surface ices, among which both simple volatile compounds and complex products of radiolytic synthesis were identified (Table 1).

Table 1 – Chemical compounds and their phase state by the features of spectral lines

Spectral range (μm)	Detected chemical compounds and phase state	Characteristic features of spectral lines	Geophysical significance and interpretation
0.9 – 2.5	Molecular nitrogen (N_2), Methane (CH_4), Deuterated methane (CH_3D), Water ice (H_2O)	Deep N_2 absorption band at 2.15 μm , prominent CH_4 and CH_3D bands.	Indicates the presence of a mobile volatile cover participating in seasonal cycles of sublimation and condensation.
2.5 – 4.5	Carbon dioxide ($^{12}\text{CO}_2$, $^{13}\text{CO}_2$), Crystalline water ice (H_2O)	More than 20 overtone and combined CO_2 absorption bands; peak at 3.1 μm .	Proves a high degree of crystallization of water ice and an anomalously high concentration of carbon dioxide compared to other TNOs.
4.5 – 4.8	Carbon monoxide (CO), Ethane (C_2H_6), Acetylene (C_2H_2)	Dense forest of atmospheric CO emission peaks; weak organic absorptions.	Testifies to active processes of ultraviolet and radiation modification of surface methane ices.

Analysis of the reflectance spectra of the opposite hemispheres of Triton – the sub-Neptunian (facing the planet) and the anti-Neptunian – revealed a pronounced longitudinal asymmetry in the distribution of the most volatile substances. The content of molecular nitrogen (N_2), methane (CH_4) and carbon monoxide (CO) was found to be systematically higher in the hemisphere that is constantly facing Neptune. This is confirmed by a significant difference in the depth of the N_2 absorption band at a wavelength of 2.15 micrometers. In contrast, less volatile compounds, such as water ice (H_2O) and carbon dioxide (CO_2), which are thermodynamically stable at Triton's

average surface temperature of ~ 38 K, are distributed extremely evenly over the surface and do not show significant long-term fluctuations.

A special discovery was the detection of intense fluorescent emission lines of gaseous CO in the infrared range between 4.5 and 4.8 micrometers. Comparison of the observed lines with theoretical models of nonlocal thermodynamic equilibrium showed significant differences in the relative intensities of vibrational transitions. This indicates the presence of complex and still poorly understood processes of uncoordinated excitation of molecules in the upper layers of the rarefied atmosphere of Triton [10, 22, 27] under the influence of solar UV radiation and charged particles from the magnetosphere of Neptune, similar to the processes in comets and the atmosphere of Pluto.

Dynamics of volatile compounds and comparative geochemical analysis with Pluto. JWST spectroscopy of Triton has confirmed the presence of a complex ice mixture on its surface, including molecular nitrogen (N_2), carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and water ice (H_2O) (Table 2). However, the real discovery is the detection of a significant deficiency of methane and enrichment in carbon dioxide compared to Pluto [19].

Table 2 – Spectral indices and compositions for Triton and Pluto according to New Horizons and JWST data

Spectral Index / Compound	Triton (JWST / NIRSpec data)	Pluto (New Horizons / JWST data)	Geochemical and geodynamic significance
N_2 Ice	Pan phase (>55%)	Dynamic phase	Major matrix carrier of volatile ices
CO_2 Ice	High concentration (10 - 20%)	Almost absent / trace amounts	Product of methane oxidation in the ocean
CH_4/N_2 Ratio	Low (10^{-3} - 10^{-4})	High (10^{-2})	Methane depletion through hydrothermal reworking
2.72 μm Band (Phyllosilicates)	Recorded on inner moons	None	Evidence for aqueous metamorphism of a silicate core
H_2O Ice	Found in solid substratum	Found as mountain ranges	Basic framework of the ice crust

According to studies in [8, 9], the relative contributions of carbon and nitrogen compounds in the surface ices and atmosphere of Triton indicate a long-term influence of endogenous water processes. While methane remains one of the dominant volatile phases on Pluto, on Triton a significant part of the primary CH_4 was chemically processed in the process of hydrothermal synthesis in the subsurface ocean. When methane interacts with hot water in the presence of catalytically active silicates, a steam conversion reaction occurs:



The hydrogen (H₂) formed in this process, due to its low molecular weight, effectively diffused through the ice crust and dissipated into space, while carbon dioxide (CO₂) accumulated in the hydrosphere and was carried to the surface by cryovolcanism [20]. This explains the high concentration of CO₂ (up to 10 - 20% of the surface coverage) on Triton and confirms that hydrothermal activity in its interior lasted much longer than in the interior of Pluto.

Mechanism of Triton capture and its initial state. There has been a long debate about the mechanism of Triton capture by Neptune. Models of capture due to aerodynamic braking in the circumplanetary gas nebula or due to direct collisions with existing satellites required unlikely coincidences. Modern dynamical modeling, first proposed in [1] and later expanded in [12], has shown that the capture occurred by the mechanism of gravitational exchange in a three-body system. Triton was originally the main component of a binary system of Kuiper belt objects (similar to the Pluto–Charon system). When the binary system approached Neptune, one of the components gained excess kinetic energy and was ejected into a heliocentric orbit, while Triton lost energy and moved into a bound highly eccentric ($e > 0.9$) retrograde orbit around Neptune.

The scheme of this process unfolded in two stages:

1. The entry of the binary system from the Kuiper Belt into the Hill sphere of Neptune with the orbital velocity of approach.
2. Gravitational filling exchange, in which the Triton companion accelerates and leaves the Neptune system, and Triton itself decelerates below the second cosmic velocity for Neptune and moves into a closed elliptical orbit with a significant initial eccentricity $e > 0.9$.

The capture into a highly eccentric orbit initiated a grandiose epoch of tidal dissipation [6, 13]. The tidal heating power during the first 100 - 300 million years after the capture was calculated by the formula:

$$\frac{dE}{dt} = \frac{21}{2} \frac{\text{Im}(k_2) G M_N^2 R_T^5 e^2}{a^6},$$

where G – is the gravitational constant, M_N is the mass of Neptune, R_T is the radius of Triton, a is its semi-major axis, e is the eccentricity, $\text{Im}(k_2)$ is the imaginary part of the 2nd-order Love number, which describes the viscoelastic rheology of the body.

This tidal heat flux exceeded even the modern heat release of Jupiter's satellite Io by several times, which led to the complete melting of Triton's hydrosphere, degassing of its interior and the destruction of any primary regular system of Neptune's satellites. However, after the circularization of the orbit ($e \rightarrow 0$), a paradox arose: exclusively radiogenic heating of the silicate core ($H_{\text{rad}} \approx (3 - 5) \text{ mW/m}^2$) was not enough to maintain a liquid subsurface ocean for 4.5 billion years without freezing. The solution to this paradox is to take into account the obliquity tides studied in [5, 11]. Since Triton's orbit has a large inclination relative to the equator of Neptune (156.8°), the satellite experiences constant periodic perturbations of its own angle of inclination of the rotation axis. Tidal dissipation, which occurs due to shear deformations in the lower viscous part of the ice crust and in the liquid ocean under the influence of obliquity

tides, provides a constant energy influx of the order of $10 - 30 \text{ mW/m}^2$. This thermal barrier prevents the ocean from freezing until the present time.

Gravitational data. The current array of experimental data on Triton's gravitational field is based exclusively on the results of the Voyager 2 spacecraft flyby in 1989. During its passage through the Neptune system, the probe's trajectory was deflected by the gravitational pull of the planet and its satellites. The radio system, by measuring the Doppler shifts of the carrier signal frequency in two bands, made it possible to determine with high accuracy the product of the gravitational constant and the satellite's mass ($G \square M$), which is $1.433 \square 10^{12} \text{ m}^3/\text{s}^2$. This corresponds to the total mass of Triton $M = (2.141 \square 0.003) \square 10^{22} \text{ kg}$, which is approximately 0.358% of the Earth's mass.

Despite the high accuracy of determining the mass and radius of the satellite, Voyager 2 made a quick single flyby, which made it impossible to directly measure the quadrupole coefficients of the second-order gravitational field (J_2 and C_{22}). For a spherical body in a state of hydrostatic equilibrium, which rotates synchronously with its orbital period ($P \square 5.877$ days), these harmonics are rigidly connected to the internal density distribution through the dimensionless moment of inertia (C/MR^2). For a homogeneous sphere, $C/MR^2 = 0.4$. In the case of Triton, this value is:

$$\frac{C}{MR_T^2} \approx 0.310 - 0.315$$

This value is significantly less than 0.4, which is mathematical evidence of a high concentration of mass in the center of the satellite and the existence of a dense silicate-metal core surrounded by a lighter ice-water shell. According to the equation relating the oblateness of the body f , its dynamic compression and the Love number k_2 , Triton is in a state close to hydrostatic equilibrium:

$$\frac{C}{MR_T^2} = \frac{2}{3} \left[1 - \frac{2}{5} \sqrt{1 + \eta} \right],$$

where the logarithmic density gradient parameter η is determined by the tidal potential of Neptune.

The constant tidal interaction with Neptune leads to deformation of Triton's shape, stretching it along the satellite–planet line and forming a permanent tidal elongation. In addition, the long-term redistribution of volatiles on the satellite's surface directly affects its inertia tensor. The constant sublimation of nitrogen ice at the equator, which receives more solar heat, and its subsequent condensation in the polar regions leads to the accumulation of excess mass at the poles.

Simulations show that the transfer of the equivalent of a 200-meter layer of ice occurs over a time of the order of 10^5 years. When polar accretion exceeds a critical limit, the equatorial moment of inertia becomes less than the moment of inertia about the axis of rotation, making the planet dynamically unstable (Table 3). This initiates a process of polar wander, returning Triton's axis of rotation to a new stable position and causing global tectonic stresses in the icy crust.

Long-term orbital studies are needed to accurately map the gravitational field and experimentally confirm the moment of inertia of Triton. Promising missions, such as the Trident concept (Discovery Program) or the large orbiter NOSTROMO, plan to measure gravitational harmonics up to the 2nd and 4th degrees using high-precision radio tuning with a velocity measurement accuracy of up to 0.015 mm/s [15].

Table 3 – Some physical and orbital parameters of Triton

Physical / Orbital Parameter of the Satellite	Numerical value of the parameter	Measurement error	Geophysical and dynamical significance
Equatorial Radius (R)	1353.4 km	□ 0.9 km	Determines total volume and is used to calculate average density.
Mean Density (□)	2061 kg/m ³	□ 32 kg/m ³	Indicates mass ratio of silicate rocks to ice as 70% to 30%.
Acceleration of Gravity (g)	0.779 m/s ²	–	Identifies low pressure gradient in the interior and hydrostatic pressure structure.
Second Gravitational Harmonic (J₂)	3.4□10 ⁻⁴ (estimate)	–	Indicates degree of equatorial bulge due to centrifugal forces.
Estimated Dimensionless Moment of Inertia (C/MR²)	0.30	(theoretical model)	Indicates high mass concentration in the center (full differentiation of the interior).
Orbital Eccentricity (e)	0.000016	–	The current orbit is almost perfectly circular, limiting the current eccentric tidal heating.

Electromagnetic sounding of the inner ocean. Triton moves in the inner magnetosphere of Neptune at a distance of 14.33 R_N. Neptune's magnetic field is characterized by a strong inclination of the magnetic dipole (47□) relative to the planet's rotation axis and a significant shift relative to the geometric center. As a result, Triton is exposed to a variable external magnetic field with two main periods: the synodic period of Neptune's rotation: T_{syn} = 14.4^h; the orbital period of Triton: T_{orb} = 141.04^h.

As estimates of electromagnetic induction sounding show, the presence of a powerful ionosphere with high conductivity (> 10⁴ Sm) on Triton screens the short-period wave of 14.4 hours, making it impossible for it to penetrate into the interior. However, the long-period wave of 141 hours freely penetrates the ionosphere and atmosphere. If there is a liquid ocean with high electrical conductivity (□ ~ 2 - 8 Sm/m due to dissolved salts of NaCl and ammonia NH₃) under the ice crust of Triton, eddy currents are induced in it. These currents generate a secondary (induced) dipole magnetic field B_{sec}, which can be recorded by future space missions. The secondary field is described by the complex response function R:

$$R(\omega) = Ae^{-i\varphi}$$

where A is the amplitude response coefficient and □ is the phase shift, which depend on the thickness of the ice crust and the electrical conductivity of the ocean.

The induction process goes through the following stages:

1. Penetration of an alternating long-period wave ($T = 141.04^h$) through the ionospheric coating of Triton.
2. Excitation of eddy currents in the highly conductive subsurface layer of the ocean ($\sigma \sim (2 - 8) \text{ Sm/m}$).
3. Generation of an induced secondary dipole magnetic field B_{sec} , the amplitude and phase of which uniquely determine the thickness of the lithosphere and the salinity of the oceanic solution.

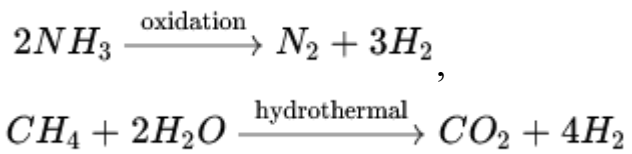
The possibility of an active internal dynamo. Thermal and geodynamic models indicate that after the era of extreme tidal heating ("hot start"), the metallic Fe-FeS core of Triton could retain enough heat to maintain convection until the present time. Top-down crystallization of the iron-sulfide melt creates compositional convection that can power an internal dynamo. This dynamo can generate Triton's own dipole magnetic field with a surface intensity of the order of $\sim 1 \text{ } \mu\text{T}$, similar to Ganymede.

Voyager 2 data clearly indicate that Triton's surface is extremely young. The low density of impact craters [2, 3, 16] and the presence of a unique "cantaloupe terrain" indicate that the average age of surface structures does not exceed 10–100 million years, and individual regions of active cryovolcanism [24] are even younger – less than 6–10 million years. However, Triton is a small body with a radius of $\sim 1353 \text{ km}$, which, according to all laws of thermal conductivity, should have completely cooled down and lost its internal energy sources billions of years ago. Traditional models of orbital evolution claimed that after the gravitational capture of Triton, its orbit should have rapidly circularized under the influence of tidal forces. The time for the decay of the eccentricity from the initial values of $e > 0.9$ to the modern almost perfect circle ($e \sim 1.6 \cdot 10^{-5}$) was estimated in the range of 10^7 to 10^8 years. Accordingly, tidal heating – the main source of internal heat – should have completely ceased at the very beginning of the history of the Neptune system. In such a scenario, the only source of energy would remain the extremely weak decay of radioactive elements in the silicate mantle, which by itself is not able to prevent the complete freezing of the subsurface ocean and maintain active cryovolcanism in the modern era. The solution to this contradiction was found only by building coupled models of thermal and orbital evolution, which take into account the dynamic feedback between the temperature of the subsurface and the rate of tidal dissipation. Using Maxwell's viscoelastic rheology to describe the behavior of ice and rocky rocks under the influence of alternating stresses, the researchers found powerful negative feedback.

The mechanism of this connection is that the initial intense tidal heating leads to the melting of the inner layers of water ice and a sharp thinning of the outer ice crust to values less than 5 km. Since the lion's share of tidal energy is dissipated precisely in the solid phase of the lithosphere (dissipation in the liquid subsurface ocean is very small), the extreme thinning of the elastic shell catastrophically reduces the physical volume of material capable of effectively absorbing and dissipating the mechanical energy of the tides. As a result, the overall rate of orbital decay (orbit circularization) drops sharply, stretching the transition to a circular orbit by billions of years.

Depending on the size of the ice grains and the viscosity of the mantle rocks, the duration of circularization according to modern calculations is from 1.2 to more than 4.5 billion years. This means that Triton's active tidal evolution continued for most of the existence of the Solar System, and the intense release of internal heat ended relatively recently or even continues today in the form of weak shear tides due to the inclination of the orbit (obliquity tides).

Additional evidence in favor of the long-term existence of internal heat sources is chemical indicators obtained from the analysis of volatile compounds on the surface of Triton. Comparative studies of the chemical composition of Triton and Pluto, conducted in [8, 9], showed that both bodies had a similar initial composition, rich in ammonia (NH₃), methane (CH₄) and carbon monoxide (CO). However, modern Triton shows a significantly higher content of molecular nitrogen (N₂) and carbon dioxide (CO₂) compared to Pluto. Geochemical modeling indicates that the long stay of nitrogen and carbon in a liquid aqueous environment in the presence of thermal flow from the hot core leads to the oxidation of ammonia to N₂, as well as the conversion of CO and CH₄ to CO₂:



The higher concentration of products of these endothermic reactions on Triton is indisputable evidence that its subsurface ocean and associated hydrothermal processes at the core-mantle boundary existed and remained active much longer than in the bowels of Pluto, which directly supports the theory of long-term tidal feeding.

Conclusions. The study of the physicochemical properties of Neptune's satellite Triton based on the latest astrophysical and geophysical data allows us to make the following generalizations. Triton is a unique differentiated body, whose multilayered structure was formed as a result of colossal tidal heating after its gravitational capture from the Kuiper belt into the retrograde orbit of Neptune. High-resolution infrared spectroscopy by the James Webb Space Telescope confirmed the presence of a complex volatile and nonvolatile cover, revealing anomalously deep carbon dioxide bands, the presence of its isotope ¹³CO₂, as well as signs of complex organic compounds and atmospheric CO fluorescence; this indicates long-term endogenous and photochemical processes. Triton's surface age (< 10 – 50 million years) confirms its modern geological and cryovolcanic activity.

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