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THERMAL AND GEOLOGICAL ACTIVITY OF NEPTUNE'S MOON TRITON.

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Abstract. Triton, Neptune's largest moon, was discovered on October 10, 1846. It is the only large moon in the Solar System that orbits its planet in a retrograde direction, with an orbital inclination of approximately 156.9° relative to Neptune's equator. This indicates that Triton is most likely a captured object that originally formed in the Kuiper Belt as part of a binary dwarf planet system. During a close encounter between this pair and Neptune, the planet's gravitational tidal forces caused the binary system to break apart; one component was ejected into interplanetary space, while Triton was captured by Neptune. In August 1989, the “Voyager 2” spacecraft performed the only close flyby of Triton. Data obtained during this mission revealed a very young surface, active cryovolcanic geysers, and a tenuous yet dynamic atmosphere. Triton's internal structure is the result of intense thermal and mechanical processing of material following its capture. With a mean radius of 1,353.4 km and a mass of 2.141×10^{22} kg, Triton exhibits a density of 2.061 g/cm^3 – a relatively high value for icy bodies. This indicates a significant proportion of silicate and metallic materials in its composition and a distinct internal differentiation of Triton into a metal-silicate core, a water-ice mantle, and a solid outer ice crust. A liquid ocean likely exists beneath the crust. The primary factors determining the thermal balance of Triton's interior are the radiogenic decay of unstable isotopes in the core and ongoing tidal heating. Tidal dissipation serves as an additional, long-term heat source, occurring primarily in the lower part of the icy lithosphere. Chemical impurities – most notably ammonia (NH_3) – play a crucial role in stabilizing the liquid phase; the presence of ammonia lowers the freezing point of aqueous solutions to as low as 176 K. Images of Triton's surface captured by the Voyager 2 spacecraft reveal an extremely low density of impact craters, indicating a high rate of geological resurfacing. The average surface age is estimated to range from 6 to 50 million years,

with some areas being even younger, making Triton one of the most geologically youthful bodies in the Solar System. Tectonic activity on Triton is also manifested through global systems of linear fractures and ridge complexes known as “sulci”. It is hypothesized that they may have formed through the multi-stage eruption of highly gas-rich cryolava via open tectonic fissures. Cryovolcanism on Triton also manifests as large, flat-floored depressions interpreted as cryovolcanic calderas or lava lakes. The most dynamic expression of Triton's current geological activity is its cryovolcanic geysers. A new phase in the study of Triton's chemical composition began in 2022 with the acquisition of the first images of the Neptune system by the James Webb Space Telescope (JWST). Spectroscopic observations by the JWST enabled a detailed analysis of absorption by various ices. These data confirm a complex evolutionary history for the body – one that originated in the transition zone of the protoplanetary disk and underwent prolonged thermal processing following its gravitational capture by Neptune.

Keywords: Triton, young surface, interior thermal balance, tidal dissipation, tectonic activity.

Introduction. Neptune's largest satellite, Triton, was discovered by the English astronomer William Lassell on October 10, 1846 – just a few days after the discovery of Neptune itself [41, 45]. Triton is unique due to its distinctive dynamic characteristics: it is the only large satellite in the Solar System that orbits its planet in a retrograde direction, along an orbit inclined at an angle of approximately 156.9° relative to Neptune's equator [49]. These features indicate that Triton could not have formed in the vicinity of the young Neptune. Most likely, the satellite is a captured object that originally formed as a dwarf planet in the Kuiper Belt [34, 38]. Calculations presented in [1] suggest that Triton was likely a member of a binary dwarf planet system [14, 32, 33, 40]. During a close encounter between this pair and Neptune, the planet's gravitational tidal forces caused the binary system to break apart; one component was ejected into interplanetary space, while Triton was captured by Neptune into a highly eccentric orbit.

The capture of such a massive body led to the destruction of Neptune's original satellite system, transforming it into a cloud of debris. Neptune's current inner satellites formed later from this cloud. Recent spectroscopic observations using the James Webb Space Telescope (JWST) have revealed [9] that the surface composition of Nereid – Neptune's third-largest moon – differs significantly from that of typical Kuiper Belt objects, showing a high water-ice content. This makes it similar to the moons of Saturn and Uranus. The data support the hypothesis that Nereid is the sole surviving regular moon of the first generation.

In August 1989, the “Voyager 2” spacecraft performed the only close flyby of Triton to date [5, 17]. The results revealed an extremely young surface, active cryovolcanic geysers, and a tenuous yet dynamic atmosphere [6, 13, 18, 42, 50]. Promising space missions to this moon are currently under development; these will reshape our understanding of the physics and chemistry of icy worlds in the outer Solar System.

Internal geological activity of the moon. Triton's internal structure is the result of intense thermal and mechanical processing of material [16, 36, 37] that occurred

following its capture. With a mean radius of 1,353.4 km and a mass of 2.141×10^{22} kg, this satellite is characterized by a density of 2.061 g/cm^3 – relatively high for icy bodies – indicating a significant proportion of silicate and metallic rock in its composition [12]. Current geophysical models predict a distinct internal differentiation of Triton into a metal-silicate core, a water-ice mantle, and a solid outer ice crust. The silicate core accounts for approximately 65–70% of the satellite's total mass.

A key question regarding Triton's internal state is the existence of a subsurface liquid ocean [7, 10, 20, 26]. Maintaining water in a liquid state for 4.5 billion years at such a distance from the Sun (30 AU) requires powerful internal heat sources and a specific chemical composition of the hydrosphere. The primary factors determining the thermal balance of Triton's interior are the radiogenic decay of unstable isotopes in the core and ongoing tidal heating. Radiogenic heating, driven by the decay of ^{40}K , ^{232}Th , ^{235}U , and ^{238}U isotopes in the rocky core, generates a steady heat flux estimated to range from $0.75 \times 10^{11} \text{ W}$ to $1.5 \times 10^{11} \text{ W}$. However, radiogenic heat alone would be insufficient to sustain a global ocean; in the absence of other energy sources, the water layer would have frozen completely within 2–3 billion years of its formation.

Tidal dissipation serves as an additional long-term heat source [8]. Although Triton's orbit is currently nearly perfectly circular (eccentricity $e \approx 0.000016$), the significant orbital inclination gives rise to substantial fluctuations in tidal forces. Tidal dissipation occurs primarily in the lower part of the icy lithosphere. This creates a "tidal blanketing" effect: heat release directly at the base of the ice shell sharply reduces the temperature gradient, thereby significantly slowing heat loss and the crystallization of the subsurface ocean.

Chemical impurities – primarily ammonia (NH_3) – play a crucial role in stabilizing the liquid phase. As a Kuiper Belt object, Triton's primordial material could have contained up to 15% ammonia. The presence of ammonia lowers the freezing point of aqueous salt solutions (specifically, the eutectic temperature of the water-ammonia mixture) to as low as 176 K. As pure water ice gradually freezes out at the crystallization front, the residual liquid ocean becomes progressively enriched with ammonia. This leads to a decrease in its viscosity, an increase in density, and enhanced gravitational drainage. This process creates a thermodynamically and dynamically stable layer of liquid water-ammonia solution, 100 to 250 km thick, beneath an ice crust 15 to 100 km thick. Table 1 presents a comparison of thermal evolution parameters for Triton's interior based on various model scenarios of internal dynamics.

Direct physical contact between the liquid ocean and the metal-silicate core creates unique conditions for heat and mass exchange. Driven by high temperatures within the core (which can reach 1,500 K), hydrothermal circulation occurs at the interface [43]. This process enriches the ocean with dissolved mineral salts, iron compounds, sulfates, and volatile gases (CO_2 , CH_4) – factors of key importance for the satellite's potential chemical evolution and habitability.

Geological activity on the satellite's surface. Images of Triton's surface captured by the "Voyager 2" spacecraft reveal an extremely low density of impact craters [4, 29], indicating a high rate of geological resurfacing. The average surface age is

estimated to range from 6 to 50 million years, with some areas (specifically the so-called "cantaloupe terrain" in the equatorial zone) dating back less than 6–10 million years. This makes Triton one of the geologically youngest bodies in the Solar System.

Cantaloupe terrain and the issue of diapirism. The most well-known and morphologically complex landscape type on Triton is the "cantaloupe terrain," which covers up to 35% of the satellite's observed surface in the northern hemisphere and equatorial region. It is characterized by a regular network of enclosed depressions – cavities ("cavi") – that are round or elliptical in shape and measure 25 to 40 km across, separated by a complex system of ridges ranging from 300 to 800 m in height.

Early studies following the "Voyager 2" flyby (notably [21]) attributed the formation of this terrain to Rayleigh-Taylor-type gravitational instability within a multilayered icy crust. According to this hypothesis, less dense water or ammonia ice rose through a layer of denser solid nitrogen or carbon dioxide (CO₂) deposits, forming dome-like structures known as diapirs. Calculations indicated that, given a temperature gradient of approximately 10 K/km, such a process could have resulted in a complete crustal overturn over a period of about 1 billion years.

Table 1. Models of the thermal evolution and state of Triton's subsurface ocean.

Model parameter	Scenario A: Radiogenic heating only (pure H₂O)	Scenario B: Radiogenic and tidal heating (pure H₂O)	Scenario C: Radiogenic and tidal heating and 1% NH₃	Scenario D: Convective shell with ammonia and methanol impurities
Liquid ocean thickness (present-day)	0 km (complete freezing in 2.5 Ga)	10–50 km (critically thin boundary)	Above 130–250 km	Over 300 km
Ice shell thickness	>350 km (solid ice)	100–150 km	15–50 km	15–30 km
Heat transport mode in the shell	Pure thermal conduction	Localized convection	Intense parameterized convection	Rapid viscoelastic deformation
Temperature at the shell-ocean interface	273 K (in the event of partial melting)	270 K	176–240 K	≈ 160–180 K
State of the ocean-core contact	Absent (complete freezing)	Direct contact at the base	Direct contact with high mineralization	Favorable for hydrothermal circulation

However, modern numerical simulations and realistic models of the viscoelastic rheology of ice mixtures at Triton's extremely low surface temperatures (38–40 K) rule out the possibility of classical diapirism. New calculations demonstrate that at these temperatures, the viscosity contrast between water ice and volatile ices is too great – spanning up to seven orders of magnitude. This effectively prevents viscous diapirs from reaching the surface. Instead, a more likely model posits that a thick (over 10 km) subsurface layer of carbon dioxide (CO₂) – lying beneath a thin nitrogen crust – undergoes intense stretching and deformation above zones of internal convection

within the water mantle. Mechanical stress reaching 4 MPa (exceeding the tensile strength of ice mixtures at low temperatures) causes deep fracturing of the upper layers. Subsequent sublimation of highly volatile nitrogen ices along these fractures, combined with the thermodynamic retreat of scarps, formed the characteristic depressions observed today as hollows.

Tectonic and cryovolcanic features. Tectonic activity on Triton is also manifested in global systems of linear fractures and ridge complexes known as “sulci”. The most thoroughly studied examples are Slidr Sulci, Boyne Sulci, and Tano Sulci. For instance, Slidr Sulci is an extensional fracture zone approximately 20 km wide and up to several hundred meters deep, consisting of a series of parallel ridges about 200 m in height. These ridges exhibit a somewhat lower albedo (by 20–50%) compared to the surrounding plains. It is hypothesized that these ridges may have formed through the multi-stage extrusion of highly gas-rich cryolava (a water-ammonia mixture) [15] through open tectonic fractures. During the initial stage of extrusion, a narrow central ridge formed; as eruptions continued, it widened and pushed apart the boundaries of the fault. An alternative view interprets these structures as compressional belts (fold belts) where ice slabs were thrust over one another due to global compression of the satellite as its interior cooled.

Cryovolcanism [35, 48] on Triton also manifests as large, flat-floored depressions interpreted as cryovolcanic calderas or cryolava lakes. The largest such feature is Leviathan Patera – a ring-like structure approximately 80 km in diameter, surrounded by radial fracture systems (Kraken Catena and Set Catena). To the west lie two giant cryolava lakes, comparable in area to, for instance, the hydrocarbon sea Kraken Mare on Titan [46, 47]. The absence of even small craters on their surfaces indicates that these basins were completely filled with a liquid or semi-liquid water-ammonia mixture in the very recent geological past.

Geysers and mechanisms of their activity. The most dynamic manifestation of Triton's current geological activity is its cryovolcanic geysers [3, 11, 27]. During the “Voyager 2” flyby in 1989, eruptions from two large active geysers – Hili and Mahilani – were recorded in the southern polar region at latitudes between 50°S and 57°S. The emissions appear as narrow vertical columns of gas and dark dust rising to an altitude of up to 8 km. At this height, they turn sharply westward at a 90° angle due to atmospheric winds, forming horizontal plumes extending over 150 km. In total, more than 120 dark fan-shaped streaks (plumes) – representing dust deposits from previous eruptions – have been mapped on the surface of the southern polar cap.

Currently, there are three main scientific hypotheses explaining this phenomenon:

The solar solid-state greenhouse effect model: This hypothesis views the geysers as a purely near-surface phenomenon driven by solar heating. Nitrogen ice on Triton is translucent to visible sunlight. Light passes through an ice layer approximately 1–2 meters thick and is absorbed by a dark organic substrate at the base of the ice sheet. This causes a localized temperature rise and intense sublimation of nitrogen beneath the ice. When gas pressure exceeds the structural strength of the ice cover, an explosive rupture occurs, ejecting gas and dark dust particles into the

atmosphere. While this model effectively explains why geysers are localized near the subsolar point, it struggles to account for the duration of eruptions (as some geysers remain active continuously throughout the year).

Endogenic cryovolcanism model: This model links the geysers to processes occurring deep within the satellite's interior. It posits that internal heat – generated by radiogenic and tidal forces – drives a pressurized mixture of water, ammonia, and volatile gases upward through crustal fractures. Upon exposure to the vacuum, dissolved gases (primarily methane and carbon monoxide) flash-boil, atomizing the liquid into fine ice crystals and dust. In this scenario, the eruptions are analogous to terrestrial volcanic eruptions and operate independently of solar illumination.

Basal melting model of the nitrogen sheet driven by internal heat: This concept represents a compromise. It suggests that localized zones of elevated geothermal flux trigger melting and convection at the base of the thick (over 100 m) nitrogen ice layer. Heated liquid or ductile nitrogen rises, causing intense sublimation and a rupture of the overlying solid crust.

To distinguish between these models, future spacecraft must conduct a series of observations, which are systematized in the following scheme.

Composition of the satellite's surface material. Triton's surface is a unique chemical reservoir where, at temperatures around 38 K, highly volatile substances in solid and gaseous states coexist with extremely strong lithospheric ices [22, 24, 25, 30, 33, 44].

Major components and their phase states. Based on ground-based infrared spectroscopy and data from the "Voyager 2" mission, the distribution of the primary ice phases on the satellite's surface is as follows:

Nitrogen ice (N₂) covers approximately 55% of the satellite's surface, forming a massive polar cap in the southern hemisphere and seasonal frost at temperate and equatorial latitudes. Nitrogen on Triton exists in a state of vapor-pressure equilibrium with its atmosphere. At 38 K, nitrogen ice exists in a hexagonal crystalline phase (beta-phase); the transition to this phase from the low-temperature cubic phase (alpha-phase) occurs at 35.6 K. Hexagonal nitrogen ice is extremely plastic, soft, and translucent, allowing solar radiation to penetrate to significant depths and create conditions for a greenhouse effect.

Water ice (H₂O) accounts for 15% to 35% of the surface. Due to the extreme cold, water ice on Triton is mechanically rigid – comparable to terrestrial granite – and serves as the "bedrock" upon which volatile ices rest. Observations indicate that it exists primarily in a crystalline state.

Carbon dioxide (CO₂) covers approximately 20% of the surface. Together with water ice, it forms a robust foundation for the satellite's crust, protected from rapid sublimation by the low saturation vapor pressure at these temperatures.

Minor constituents (methane CH₄, carbon monoxide CO) are present either as isomorphous impurities within the nitrogen ice matrix or as distinct patches (maculae) [23].

All the aforementioned compounds are subject to intense radiolytic, and photochemical processing driven by solar UV radiation and charged particles from

Neptune's magnetosphere [28, 31]. This leads to the formation of complex organic compounds known as tholins (complex nitrogen-carbon macromolecules), which impart a characteristic pink or reddish-brown hue to certain regions of Triton (particularly equatorial zones and areas where geyser deposits accumulate).

Spectroscopic observations using the JWST. A new phase in the study of Triton's chemical composition began in September 2022 with the acquisition of the first images of the Neptune system using the James Webb Space Telescope (JWST). Thanks to the sensitivity of the NIRCam and NIRSpec instruments in the near-infrared range (0.6–5.3 μm), it was possible to obtain high-precision, spatially resolved spectra of Triton for the first time. In JWST infrared images, Triton appears significantly brighter than Neptune itself. The reason for this lies in the selective absorption of light by the planet's atmosphere. Neptune's atmosphere contains large amounts of methane, which strongly absorbs light at wavelengths between 1 and 5 μm , rendering the planet extremely dark. In contrast, Triton – covered in highly reflective ices – reflects up to 70% of incident light, creating the appearance of an exceptionally bright object.

JWST spectroscopic observations enabled a detailed analysis of absorption by various ices. The presence of crystalline water ice was conclusively confirmed by a deep absorption band at 1.5 μm , a distinctive crystalline feature at 1.65 μm , and a narrow Fresnel peak at 3.1 μm . Additionally, a deep water-ice combination band at 4.5 μm was detected for the first time. JWST analysis made it possible to compare Triton with various compositional classes of Kuiper Belt Objects (KBOs) [2]. The large-scale DiSCo (Discovering the Surface Composition of Trans-Neptunian Objects) survey established the existence of three spectral classes among KBOs (Table 2).

Table 2: Spectral classes of Kuiper Belt objects and Triton's position based on JWST data.

TNO spectral class	Key chemical markers	Spectral characteristics	Representatives of the class	Triton's characteristics relative to the class:
"Bowl" class (water-rich)	Water ice (H_2O), crystalline phase, dark carbonaceous regolith.	Deep water-ice bands, low visible-light albedo.	Haumea, Quaoar, Charon, small Centaurs.	Triton exhibits similar deep H_2O absorption bands in its crustal bedrock.
"Double-dip" class (carbon dioxide-rich)	Carbon dioxide (CO_2), some complex organic tholins.	Strong double CO_2 absorption bands.	Large classical TNOs.	Triton possesses extensive CO_2 -ice fields integrated into its lithosphere.
"Cliff" class (methanol-rich)	Complex organic molecules, methanol (CH_3OH), nitrogen compounds.	Red color in the visible range, specific methanol bands.	Makemake, Eris.	Triton shows the presence of complex tholins and nitrogen-bearing compounds.

It turns out that Triton combines spectral features of all three fundamental classes, confirming its complex evolutionary history as an object that originated in the transition zone of the Sun's protoplanetary disk and underwent prolonged thermal processing following its gravitational capture by Neptune.

Conclusions. Thus, Neptune's satellite Triton is a unique object in the Solar System, combining characteristics of Kuiper Belt dwarf planets with extreme geophysical and climatic dynamics driven by gravitational capture. Its retrograde orbit and tidal heating characteristics led to complete internal differentiation and created conditions for a global subsurface water-ammonia ocean in direct contact with a metal-silicate core.

Triton's modern geological structures – ranging from "cantaloupe terrain" formed by mechanical stress and selective ice sublimation to active cryovolcanic geysers and young lava lakes – indicate that it is one of the most energetically active bodies in our Solar System. Recent spectroscopic observations using the James Webb Space Telescope have significantly refined our understanding of its crust's chemical composition, confirming that Triton originated within the system of trans-Neptunian objects. Several specialized space missions designed to enter Triton's orbit are planned for the coming decades. These include the Triton Ocean World Surveyor mission and flagship-class missions such as Neptune Odyssey [19].

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ОСОБЛИВОСТІ ВИБОРУ ШАРУ ІНІЦІАЛІЗАЦІЇ ε-СИЛЬНОГО МОДЕЛЮВАННЯ

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Анотація. Розглянуто етап ініціалізації ϵ -сильного моделювання вінерівського процесу: побудову початкового шару обмежувальних коридорів броунівського моста, що з'єднує вузлові точки траєкторії процесу Вінера. Досліджено очікувану тривалість вибору шару залежно від його ширини $h = h(T, \Delta X)$. Для певного набору параметрів визначено межу коефіцієнта пропорційності, за якої вибір шару з високою частотою відбувається за зівставний час для широкого діапазону значень.

Ключові слова: процес Вінера, броунівський міст, ϵ -сильне моделювання, шар ініціалізації, крок дискретизації.

Введення. Під час застосування методу Монте-Карло для оцінки очікуваних значень різних функціоналів від процесу Вінера, таких як, наприклад, часу перебування траєкторії над рівнем, класичний підхід моделювання значень цієї траєкторії в точках рівномірного розбиття часового проміжку може призводити до систематичного зсуву. Дискретна апроксимація процесу Вінера випадковим блуканням формує можливість "пропуску" моменту перетину рівня