Fundamental Research 6 (2026) 2803–2811

Contents lists available at ScienceDirect

Fundamental Research

journal homepage: http://www.keaipublishing.com/en/journals/fundamental-research/

Review

Triton as an archetype for icy ocean worlds: Key scientific drivers for future exploration ☆

Chi Wang [a,b,*], Hui Li [a,c,*], Yuxian Wang [a,b], Jiansen He [a,d], Jihua Hao [e,f], Ranran Liu [g], Jiaqi Li [d], Bingkun Yu [e], Hui Huang [e], Weiyi Zheng [a,b]

[a] State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
[b] College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 101408, China
[c] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 101408, China
[d] School of Earth and Space Sciences, Peking University, Beijing 100871, China
[e] Institute of Deep Space Sciences, Deep Space Exploration Laboratory, Hefei 230088, China
[f] National Key Laboratory of Deep Space Exploration, University of Science and Technology of China, Hefei 230026, China
[g] State Key Laboratory of Atmospheric Environment and Extreme Meteorology, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

ARTICLE INFO

Article history:
Received 30 September 2025
Received in revised form 15 July 2026
Accepted 17 July 2026
Available online 22 July 2026

Keywords:
Extraterrestrial life
Habitability
Icy satellites
Triton
Ocean worlds

ABSTRACT

Ocean worlds (a subset of icy satellites) are among the most promising targets in the search for extraterrestrial habitability and biosignatures. Triton stands out due to its capture from the Kuiper Belt, geological activity, and potential subsurface ocean. This article reviews global efforts in icy satellite exploration and identifies three key scientific themes for Triton: Subsurface Ocean and Habitability, Extent of Interior-Surface-Atmosphere Coupling, and Dynamic Space Environment. We assess the current state of knowledge and highlight critical unresolved questions for future missions. By analyzing the Neptune-Triton system and emerging trends in planetary exploration, we propose scientific investigations and recommendations for future exploration of Triton. Payload requirements are outlined to investigate Triton's potential habitability, subsurface ocean, atmosphere, and surrounding space environment. A comprehensive, multi-instrument, and potentially multi-platform approach is essential to achieve transformative discoveries. This synthesis provides a scientific framework to guide future exploration, particularly informing the planning of China's upcoming deep space missions to ocean worlds.

1. Introduction

The search for extraterrestrial life and the study of planetary habitability represent a core frontier in planetary science and astrobiology, addressing fundamental questions concerning the origin of life and its prevalence in the cosmos, with profound philosophical and strategic significance. With the breakthrough discovery of global subsurface liquid oceans on icy satellites by deep-space missions such as Voyager 2 and Cassini, the research strategy dominated by "Follow the Water" has gradually shifted from focusing on surface geological evidence of liquid water to a systematic exploration of three-dimensional, dynamic ocean worlds [1,2].

Within the Solar System, the search for life prioritizes targets that possess key habitability characteristics, including appropriate size and mass, the presence of liquid water, a suitable temperature range, a stable atmosphere, effective magnetic shielding, a moderate radiation environment, and essential chemical elements. Life as we know it requires three fundamental ingredients: liquid water, an energy source, and organic building blocks [2,3]. However, their mere presence is insufficient without long-term environmental stability, which is crucial for maintaining habitable conditions over geologic time. The Venusian atmosphere, the Martian surface, and the subsurface liquid oceans of icy satellites have emerged as prime targets in the search for extraterrestrial life due to their potential habitability [3,4].

Some icy satellites are composed primarily of ice and rock, structured with a rocky or metallic core, a global or regional subsurface liquid ocean, and an outer ice shell. Their surface ice is not limited to water ice but may also contain condensates of volatiles such as nitrogen (N_2), methane (CH_4), and ammonia (NH_3) [1,2]. Icy satellites are prevalent throughout the Jovian, Saturnian, Uranian, and Neptunian systems. The primary motivation for investigating icy satellites lies in their immense astrobiological potential. Internal heat sources, predominantly tidal heating and radiogenic decay, sustain subsurface liquid water oceans over geologic timescales. Analogous to Earth's deep-sea

☆ Peer review under the responsibility of Editorial Board of Fundamental Research.

* Corresponding authors.
E-mail addresses: cw@swl.ac.cn (C. Wang), hli@swl.ac.cn (H. Li).

https://doi.org/10.1016/j.fmre.2026.07.004
2667-3258/© 2026 The Authors. Publishing Services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

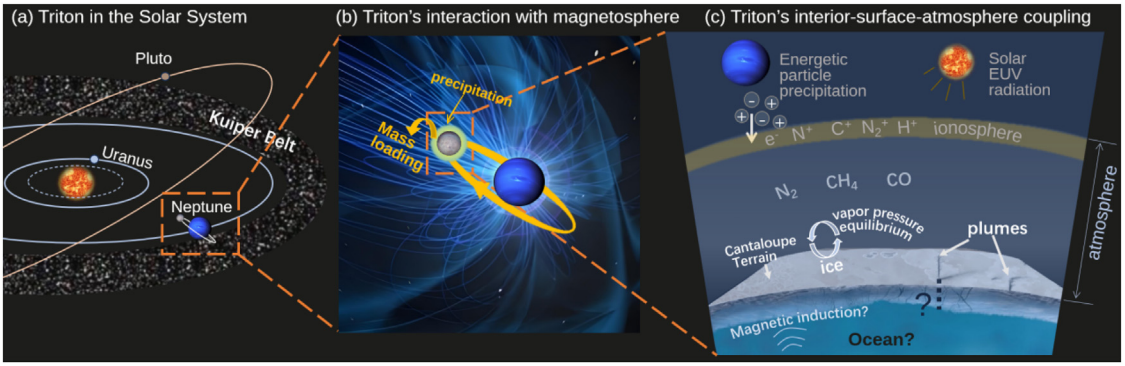


Fig. 1. (a) Triton's orbital location in the Solar System. (b) Schematic of Triton's interaction with Neptune's magnetosphere. (c) Triton's coupled interior-surface-atmosphere system.

environments, these hidden oceans may host ecosystems driven by geological activity and chemolithoautotrophic cycles independent of solar illumination [1]. Hydrothermal activity at the seafloor, akin to terrestrial "black smoker" vents, can continuously supply chemical energy and essential nutrients, providing the basis for chemosynthetic ecosystems and creating favorable conditions for the emergence and maintenance of life [1].

The existence of subsurface oceans can be inferred through multi-instrument observations, including surface geological activity (e.g., plume eruptions, tectonic deformation), surface chemical composition, orbital dynamics and rotational anomalies, tidal responses, and electromagnetic induction signatures. To date, substantial evidence confirms the presence of subsurface oceans in Europa, Ganymede, Callisto and Enceladus. Additionally, Triton, Pluto, the Uranian moons Ariel and Miranda, and the dwarf planet Ceres are considered potential ocean worlds, awaiting further verification through future missions [1,5].

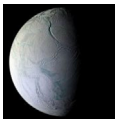
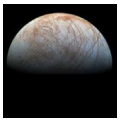
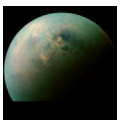
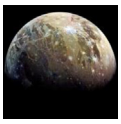
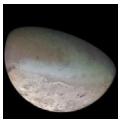
Triton, Neptune's largest moon, is the only known large satellite in the Solar System with a retrograde orbit, strongly indicating its origin as a captured Kuiper Belt object (KBO) [6,7]. The 1989 flyby by Voyager 2 revealed Triton's remarkably dynamic surface: geologically young with few impact craters, and featuring active cryovolcanic plumes ejecting material kilometers into space, evidence of ongoing internal heat and mass transport. Combined with thermal evolution models of its capture-induced tidal heating, these observations strongly suggest the presence of a persistent subsurface liquid water ocean beneath its ice shell [8]. As such, Triton embodies a unique combination of a primordial outer Solar System body, a potential ocean world, and a geologically active satellite, making it one of the most compelling targets for astrobiological and habitability studies (see Fig. 1) [8,9].

In this review, we provide a comprehensive summary of research advances on icy satellites, with a focus on Triton as a priority target for China's future exploration of the icy giants. Section 2 reviews the status of past and planned icy satellite missions worldwide. In Section 3, we categorize the key scientific questions surrounding icy satellites into three themes: Subsurface Oceans and Habitability, Extent of Interior-Surface-Atmosphere Coupling, and Dynamic Space Environment. Section 4 briefly evaluates three representative mission architectures. Finally, we propose prospects and potential directions for future exploration.

2. Icy satellite exploration

Since the 1970s, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have conducted numerous deep-space missions targeting icy satellites in the Solar System (Table 1). These missions have yielded groundbreaking insights into the geological structures, internal compositions, surface chemistries, subsurface ocean characteristics, and potential habitability of these bodies [1,2]. Key missions include Voyager 1 and 2, Galileo, Cassini, New Horizons, and Juno, as well as currently operational or upcoming missions such as the JUpiter ICy moons Explorer (JUICE), Europa Clipper, and Dragonfly. In the remainder of this section, we provide a concise overview of the current state of exploration and key scientific findings for several representative icy satellites.

Table 1
Overview of the icy satellite exploration missions.

Target		Mission (Launch date)
Enceladus		Cassini-Huygens (1997, NASA/ESA), L4 (2042, ESA)
Europa		Galileo (1989, NASA), New Horizons (2006, NASA), Juno (2011, NASA), Europa Clipper (2024, NASA), JUICE (2023, ESA)
Titan		Voy1 (1977, NASA), Cassini-Huygens (1997, NASA/ESA), Dragonfly (2028, NASA)
Ganymede		Voyager 2 (1977, NASA), Galileo (1989, NASA), JUICE (2023, ESA)
Callisto		Galileo (1989, NASA), Juno (2011, NASA), JUICE (2023, ESA), Tianwen-4 (~2030, China)
Triton		Voyager 2 (1977, NASA)

(1) Enceladus

The Cassini-Huygens mission revolutionized our understanding of Saturn's moon Enceladus by discovering active plumes erupting from its south polar terrain [10]. These plumes consist primarily of water vapor and ice particles, along with significant amounts of carbon dioxide (CO_2), trace organic compounds, salts, ammonia (NH_3), and, most recently, phosphates [11]. Compositional data, together with measurements of librations, provide evidence for a global, salty subsurface ocean

beneath Enceladus's icy crust, which appears to contain nearly all the essential ingredients for life [1,12]. To assess the habitability of Enceladus and search for evidence of life, the flagship-class mission concept Orbilander has been recommended; it would conduct sustained orbital reconnaissance followed by a surface landing [13,14]. In addition, the Decadal Survey identified Enceladus as a potential target for a New Frontiers-class mission [13]. More recently, ESA announced the L4 mission as the first flagship mission of Voyage 2050, which is set to land on Enceladus [15].

(2) Europa

NASA's Galileo mission (launched in 1989) provided the first compelling evidence for a global subsurface ocean beneath Europa's icy shell, derived from imaging of surface geology [16] and detection of an induced magnetic field [17]. While transient plume activity has been inferred from Galileo data [18], extensive searches by the James Webb Space Telescope (JWST) have found no trace of such plumes [19]. Morphological features such as linea have been interpreted as possible sites of icy subduction [20]. During its 2007 Jupiter flyby, the New Horizons mission obtained high-resolution images of Europa's surface, resolving complex tectonic features [21]. The Juno mission (launched in 2011) executed close flybys of Europa, returning the highest-resolution images of portions of its surface to date and collecting valuable data on its interior structure, surface composition, ionosphere, and interactions with Jupiter's magnetosphere [22]. The Hubble Space Telescope also observed water vapor plume activity from Europa's southern hemisphere in 2012 [23]. Building on these findings, NASA's Europa Clipper mission (launched in 2024) is specifically designed to evaluate Europa's habitability by characterizing its interior structure, composition, and geology [24]. Complementing this effort, ESA's JUICE mission (launched in 2023) will also conduct two flybys of Europa as part of its broader investigation into the habitability of Jupiter's icy satellites and the formation mechanisms of the outer Solar System [25,26].

(3) Titan

Titan remains the most extensively explored icy satellite in the Solar System. During its 1980 flyby, Voyager 1 revealed a nitrogen-dominated atmosphere on Titan, with minor abundances of argon (Ar) and methane (CH_4), a surface pressure of ~1.5 bar, and a temperature of ~94 K [27]. In addition, trace complex organics (such as C_2H_4 and HCN) were detected in the stratosphere [28]. The Huygens probe, part of the Cassini mission, provided the first in situ measurements of the vertical structure and composition of Titan's atmosphere during its 2.5-h descent in 2005 [29]. Early analysis of Cassini data, including tidal response [30] and obliquity [31], suggests the presence of a subsurface ocean beneath Titan's surface. However, a recent study argues that the observed strong tidal dissipation is inconsistent with conventional liquid ocean scenarios [32]. Thus, the existence of a subsurface ocean on Titan remains an open and debated question. The Cassini orbiter further characterized the composition [33] and dynamics [34] of Titan's atmosphere over the course of 127 flybys. Building on this legacy, NASA's Dragonfly mission aims to investigate Titan's prebiotic organic chemistry, surface-atmosphere interactions, and potential habitability by exploring diverse geological environments where methane or water could act as solvents [35].

(4) Ganymede

Ganymede is the largest moon in the Solar System and the only known satellite with an intrinsic magnetic field. Voyager 2 first observed the moon's complex icy surface in 1979 [36]. Magnetic field measurements from the Galileo spacecraft during its flybys of Ganymede since 1996 revealed an induced magnetic response, providing the first evidence for a subsurface liquid water ocean [37]. Later, HST observations of suppressed auroral oscillations on Ganymede offered independent confirmation of the ocean's existence [38]. Building upon these discoveries, the JUICE mission designates Ganymede as its primary science target, aiming to characterize the moon's subsurface ocean and elucidate its formation and evolutionary history. The mission will also conduct comparative investigations of Europa and Callisto, focusing on key astrobiological prerequisites such as the distribution of organic molecules, the origin of surface geological features, and ice shell dynamics [25,26].

(5) Callisto

Callisto, the outermost of the Galilean satellites, is considered a candidate ocean world, though its putative subsurface ocean remains poorly characterized. Galileo's magnetometer detected an induced magnetic response at Callisto that could arise from either a subsurface ocean [39] or Callisto's ionosphere [40]. Recent reanalysis of Galileo data using the multifrequency magnetic induction method concludes that a subsurface ocean is most likely present [41]. Critically, Callisto appears to be not fully differentiated [42], which if confirmed, would place strong constraints on its accretion history [43]. However, this conclusion relies on the assumption of hydrostatic equilibrium, which has not yet been definitively demonstrated for Callisto [44]. HST observed Callisto's auroral footprint [45]. Juno also investigated Callisto's interaction with Jupiter's magnetosphere [46]. Due to its distant orbit from Jupiter, Callisto experiences minimal tidal heating, severely limiting material and energy exchange between its interior and surface. This makes Callisto an extreme end-member in the spectrum of ocean worlds, providing critical constraints on the ability of planetary bodies to sustain subsurface liquid water oceans under extremely low tidal energy input [1]. The JUICE mission will characterize Callisto's interaction with the Jovian magnetosphere, determine the magnetic induction response from Callisto's subsurface ocean [25], and investigate its surface and near-surface atmosphere [26]. Notably, China's recently released "National Space Science Mid- and Long-Term Development Plan (2024–2050)" identifies the Tianwen-4 mission (planned for launch around 2030) as a key initiative to investigate Callisto's ice shell morphology, surface geology, and potential subsurface ocean, significantly advancing our understanding of this ancient and enigmatic icy satellite.

(6) Triton

To date, exploration of Triton, Neptune's largest moon, has relied exclusively on the 1989 Voyager 2 flyby, the only close encounter with this potential captured KBO. Voyager 2's imaging and in situ measurements revealed a geologically young and active surface, characterized by a scarcity of impact craters, extensive "cantaloupe" terrain, and evidence of intermittent nitrogen-driven plumes [47]. However, it remains unclear whether these plumes are driven by shallow solar heating of subsurface nitrogen ice or by deeper processes potentially linked to a subsurface ocean [48]. Triton's subsurface ocean lacks direct observational evidence. Instead, its existence is primarily inferred from thermal models suggesting that radiogenic heating alone, regardless of whether Triton accreted hot or cold, would be sufficient to maintain an ocean to the present day [49]. If significant, tidal heating would further enhance ocean longevity. Together with thermal modeling that permits a long-lived subsurface ocean, Triton's geologically active surface and dynamic nitrogen atmosphere position it among the most compelling icy worlds in the outer Solar System.

To address these key questions, NASA proposed the Discovery-class mission concept "Trident" in 2020, specifically designed for a single, high-value flyby of Triton [50]. Although not selected (it was one of four finalists), Trident aimed to resolve four science questions: (1) Is Triton an ocean world? (2) What processes resurface Triton? (3) What drives Triton's plumes? and (4) Why is Triton's ionosphere so intense? Concurrently, ESA has explored mission concepts such as ODINUS (Origins, Dynamics, and Interiors of Neptunian and Uranian Systems), which

envisions twin spacecraft orbiting Uranus and Neptune to enable comparative studies of their atmospheres, magnetospheres, and satellite systems, including Triton [51]. Triton is ranked as the highest-priority ocean world for future spacecraft exploration in NASA's Roadmap to Ocean Worlds [1]. Furthermore, Neptune Odyssey, a flagship-class concept proposed in the "Planetary Science and Astrobiology Decadal Survey" [13] and ranked behind the Uranus Orbiter & Probe for practical rather than scientific reasons, also prioritizes Triton as a key target for understanding captured KBOs, active icy satellites, and the diversity of ocean worlds [8].

In summary, Triton is now a high-priority target for both planetary science and astrobiology, particularly for understanding its mysterious subsurface ocean and potential habitability. Recently, the investigation of icy satellites and the potential habitability of ice giant environments was identified as a key scientific priority in China's first national space science strategy, the National Space Science Mid- and Long-Term Development Plan (2024–2050), released in October 2024. The plan outlines that during its second implementation phase (2028–2035), China will conduct scientific feasibility studies and preparatory work for a dedicated mission to explore giant planet systems. A comprehensive mission to an ice giant system is both timely and scientifically compelling. Existing scientific evidence strongly supports prioritizing the Neptune-Triton system as the primary target for such a mission [7].

3. Science themes for icy satellite exploration

3.1. Theme 1: Subsurface oceans and habitability: the quest for life's ingredients

As outlined in Section 1, strong evidence confirms subsurface oceans on Europa, Ganymede, Callisto and Enceladus, while the presence of oceans on Triton, Titan, Pluto, Ceres, and Mimas remains unconfirmed [1,5]. Some icy satellites, such as Enceladus, even exhibit ongoing hydrothermal activity [12]. In the absence of sufficient solar energy, these liquid water environments are primarily powered by internal radioactive decay and/or tidal dissipation (in icy satellites) [52]. Compared to inner solar system bodies, these small icy bodies are generally thought to accrete higher abundances of organics and bio-essential nutrients (e.g., S and N) during their formation [1]. Consequently, these subsurface oceans are of high astrobiological interest, and their discovery has significantly expanded the traditional concept of the Goldilocks habitable zone [1,3].

Among these ocean worlds, Triton remains highly enigmatic due to a scarcity of mission data, with current knowledge relying almost exclusively on Voyager 2 observations. Triton is considered a candidate ocean world, primarily based on limited Voyager 2 observations that revealed active plumes, smooth walled plains, and the distinctive "cantaloupe" terrain [1,47]. These surface features are suggestive of internal convection and ongoing geological activity. Since all known life on Earth relies on liquid water, confirming and characterizing a potential subsurface ocean has become a primary objective of any future mission to Triton.

Triton is widely considered a dwarf planet likely from the Kuiper Belt that was captured in the early stages of the solar system, given its retrograde and highly inclined orbit [7]. This capture is thought to have occurred via the dissociation of a primordial binary system during a close encounter with Neptune [6]. Models suggest that radiogenic heating may have sustained a global ocean on Triton to the present day [52]. Further evidence comes from Triton's remarkably low topographic relief [53]. The persistence of this ocean may be further prolonged by obliquity tides and antifreeze solutes such as NH_3 and salts, which lower the freezing point [49,52]. In the interior, Triton may contain high contents of organics from its accretion materials [52]. Moreover, photochemical models suggest the active production of organic hazes on its surface [54]. Ground-based observations have detected CO_2, CH_4, and tentative signatures of HCN and C_2H_6 [55,56], and JWST has identified CO, C_2H_6, H_2O, and C_2H_2 [57]. However, no spectral confirmation of salts or complex organic macromolecules on Triton's surface has yet been achieved.

The above discussion has summarized several outstanding questions for future missions (see Fig. 2): (1) Does a global ocean currently exist on Triton, and what is its evolutionary history? (2) What are the dominant energy sources sustaining the ocean? (3) What are the physicochemical properties (e.g., depth, thickness, electrical conductivity, chemical composition, pH, and redox state) of the subsurface ocean? (4) Is the ocean environment habitable for life as we know it? (5) Are there detectable biosignatures or evidence of potential biological activity?

3.2. Theme 2: Extent of interior-surface-atmosphere coupling

Triton is believed to possess a differentiated interior comprising a rocky/metallic core, a silicate-rich mantle, a global subsurface ocean, and an overlying outer ice shell [2,52]. Radiogenic heating in the core, combined with tidal dissipation driven by Triton's orbital evolution, likely provided the sustained thermal energy necessary to maintain liquid water beneath the ice shell over geologic timescales [49]. The thickness of this ice shell is estimated to range from tens to over one hundred kilometers, depending on the efficiency of heat transport and the abundance of antifreeze solutes such as ammonia and salts [49,52]. Constraining this layered internal architecture, particularly the existence and properties of a global ocean, remains a central scientific objective for future missions to Triton.

Voyager 2 imaging revealed active nitrogen geysers and surface features indicative of cryovolcanism, making Triton one of the few bodies in the Solar System where ongoing surface activity has been directly observed [47]. These plumes, likely driven by the sublimation of nitrogen ice and potentially linked to endogenic heating, suggest possible ongoing material exchange between the interior and the surface [48]. In contrast to Europa and Enceladus, whose surfaces are dominated by water ice, Triton's surface is mainly composed of nitrogen (N_2), water (H_2O), carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) ices [51]. Together, geological resurfacing, cryovolcanism, and tectonic deformation point to a dynamic system capable of transporting volatiles and potentially bioessential materials among the interior, surface, and atmosphere. This interpretation is supported by distinct surface features: the "cantaloupe" terrain, likely indicative of convective overturn [58], and tectonic features similar to Europa's double ridges [59]. Further supporting evidence comes from Triton's remarkably young surface; crater-count analyses yield an estimated resurfacing age of approximately 100 million years [9]. Collectively, these observations imply that geological activity has persisted into the recent past and may continue to the present day.

During the 1989 Voyager 2 flyby, Triton's atmosphere was found to be predominantly composed of N_2, with trace amounts of CH_4 near the surface, where the pressure was approximately 1.4 Pa and the temperature about 38 K [60]. At least four active geyser-like plumes were observed; two of them lofted dark material up to ~8 km above the surface before high-altitude winds transported it over 100 km downwind [47,61]. Analysis of surface streaks and plume tails indicated that wind directions at different altitudes vary, with estimated speeds of 5–15 m/s [62]. Despite the tenuous atmosphere, bright clouds were detected below 4 km and a pervasive haze extended up to ~30 km [47]. Triton's atmospheric nitrogen is likely in vapor pressure equilibrium with surface nitrogen ice and is replenished through sublimation [60]. Furthermore, plume activity injects substantial amounts of gas and ice particles into the atmosphere [61], and observations revealed other types of complex interactions between the surface and the atmosphere [63].

In summary, key scientific questions regarding Triton's coupled system remain: (1) What are the characteristics of the internal structure (e.g., the composition and thickness of each layer), the ejected plumes and their associated subsurface ocean, and the neutral atmosphere? (2)

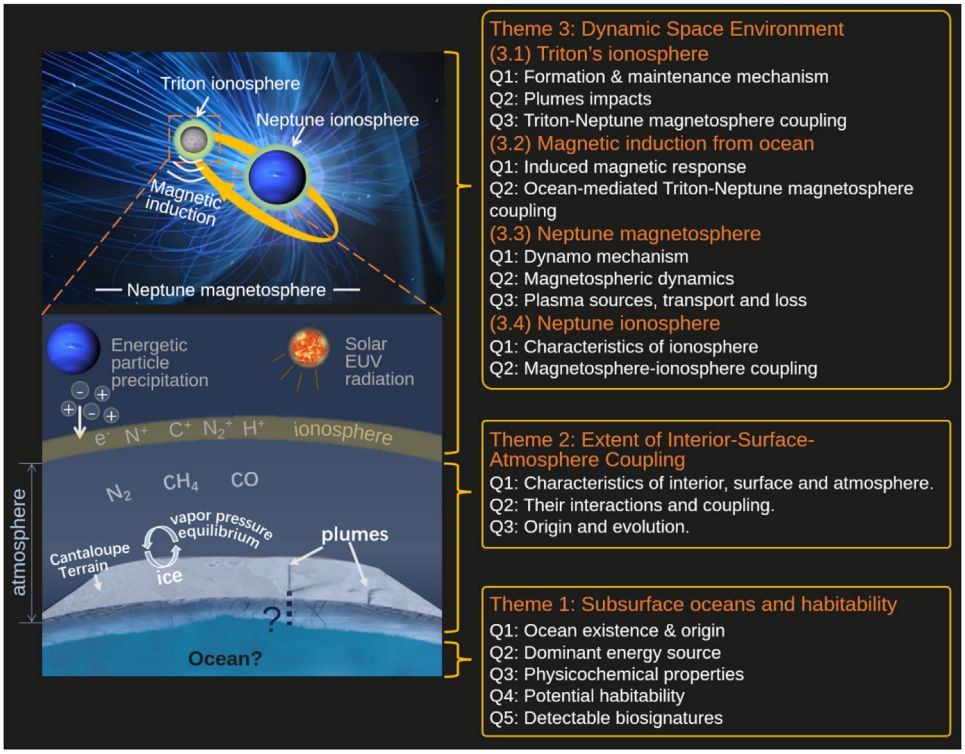


Fig. 2. Diagram illustrating the three key scientific themes identified for Triton: (1) subsurface ocean and habitability, (2) extent of interior-surface-atmosphere coupling, and (3) dynamic space environment.

How do the interior, surface, and atmosphere (i.e., internal heating and dynamics, active plumes, surface ice sublimation and atmospheric condensation, and atmospheric ionization driven by solar radiation and energetic particle precipitation) interact and become coupled across different layers? (3) How does this complex, multi-scale coupled system form and evolve over time?

3.3. Theme 3: Dynamic space environment

3.3.1. Triton's ionosphere

Voyager 2 confirmed that Triton hosts a tenuous nitrogen (N_2)-dominated atmosphere with trace methane (CH_4) and carbon monoxide (CO), and revealed a surprisingly dense ionosphere with a peak electron density of ~10^{10} m^{-3} at ~350 km altitude, decreasing sharply below 200 km [60,64,65]. Photochemical models suggest dominant ions include C^+, N^+, N_2^+, and H^+, produced by CH_4 photolysis, N_2 photoionization and electron-impact ionization by magnetospheric electrons, N_2^+ dissociative recombination, and atomic nitrogen chemistry [66]. However, solar photoionization alone cannot account for the high ionization, as Triton's peak density exceeds Titan's despite its greater solar distance [50,66]. Simulations and observations indicate that precipitation of energetic magnetospheric electrons dominates atmospheric ionization, with an ionization rate ratio of ~8:3 relative to solar EUV radiation [66]. This particle-driven mechanism likely sustains Triton's dense ionosphere and may produce EUV auroral emissions, representing the first detection of satellite-induced auroras in a corotating magnetosphere [9]. Through magnetosphere-ionosphere coupling, Triton can also generate auroral spots in Neptune's upper atmosphere [8,9].

The interaction between Triton and its surrounding space environment is bidirectional. Atmospheric sputtering and ion escape from Triton supply significant plasma to Neptune's magnetosphere [67,68]. The sputtering of Triton's atmosphere by Neptune's magnetospheric plasma can lead to an N_2 escape rate as high as 10^{24} s^{-1} [67]. Voyager 2 detected increasing densities of protons and heavy ions (likely N^+) near Neptune, suggesting a local source. Neutral particles from Triton and Neptune form a neutral torus, which ionizes to produce H^+ and N^+, contributing to a partial, non-closed plasma torus near Triton's orbit [68]. Centrifugal and magnetic forces confine these ions in a plasma sheet, enhancing density at Triton's orbital crossing. However, Triton's inclined orbit and Neptune's highly variable magnetosphere challenge the torus's stability and longevity. Plasma transport and loss mechanisms remain poorly constrained [68].

In summary, our current understanding relies heavily on Voyager 2's brief flyby and simplified models. Consequently, many key questions remain unresolved: (1) What are the precise formation and maintenance mechanisms of the highly conductive ionosphere? What are the quantitative roles of magnetospheric particle and energy inputs in ionosphere formation? (2) How do cryovolcanic plumes affect atmospheric and ionospheric chemistry? (3) What are the details of the electromagnetic coupling between Triton and Neptune's magnetosphere? Resolving these questions is crucial for understanding Triton's interior-surface-space environment coupling and its potential subsurface ocean.

3.3.2. Induction magnetic field from the subsurface ocean

Time-varying planetary magnetic fields induce electric currents in icy satellites, generating a diagnostic electromagnetic induction signature that constrains the presence, depth, and salinity of subsurface oceans [69,70]. For example, Galileo's magnetic field measurements revealed distinct induced responses at Europa, Ganymede, and Callisto, providing compelling evidence for global, highly conductive subsurface saline oceans [17,39]. While this electromagnetic method accurately gauges the product of electrical conductivity and thickness of the subsurface ocean, the interpretation is limited by an inherent degeneracy between these two factors. Complementing this method, seismology provides a critical and independent constraint on ice-shell thickness, thereby enabling a more robust and comprehensive characterization of subsurface oceanic systems [71,72]. In addition, numerical models that incorporate the moon's internal structure, its induced magnetic field, and the coupling among its atmosphere, ionosphere, and magnetosphere provide valuable constraints on ocean parameters.

However, this electromagnetic method is complicated by Triton's dense ionosphere, which mediates strong coupling among its neutral atmosphere, active plumes, and the surrounding magnetospheric plasma. Electrical currents in both the ionosphere and a putative subsurface ocean generate significant perturbations in the local magnetic field, obscuring the ocean's induction signature [40,73]. Robust detection therefore demands simultaneous, multi-instrument measurements (e.g., three-dimensional magnetic fields, plasma densities, and ionospheric currents) and their integration with advanced numerical inversion techniques, interior structure models, and orbital dynamics data to disentangle internal induction signals from external magnetospheric contributions.

In summary, critical outstanding questions for confirming and characterizing a putative subsurface ocean on Triton through magnetic induction include: (1) Does Triton currently host a subsurface ocean, and if so, how does its induced magnetic signal respond to Neptune's highly dynamic and asymmetric magnetosphere? (2) How does the conductive ocean mediate electromagnetic coupling between Triton's ionosphere and the surrounding magnetospheric plasma, and what distinct signatures does this coupling imprint on the local magnetic environment?

3.3.3. Neptune magnetosphere

Neptune's intrinsic magnetic field is highly asymmetric and non-dipolar, with a quadrupole moment comparable to its strongly tilted (46.8°) and offset (0.55 R_N) dipole [68]. This unusual geometry implies a complex dynamo [68], possibly operating in a thin shell within a deep conducting layer [51]. Limited Voyager 2 data constrain spherical harmonic models only to degree 8, suggesting higher-order moments that may be significant near the surface [74]. A full understanding requires better constraints on interior structure, composition, and fluid dynamics [9].

The large misalignment between magnetic and rotational axes drives extreme diurnal reconfigurations of the magnetosphere, cycling between a pole-on configuration with a twisted tail and an Earth-like state each rotation [74]. Voyager 2 detected a tenuous plasma populated by both light ions (likely planetary) and heavy ions (possibly from Triton), indicating Triton's influence on magnetospheric composition and a potential N^+ torus [68,74]. Neptune hosts the Solar System's weakest yet most structurally complex radiation belts [68] and exhibits ultraviolet, radio, and near-infrared aurorae [60,75], though their drivers are poorly understood. The solar wind dominates energy input, driving magnetopause Kelvin-Helmholtz instability and controlling mass/energy transport [68,74], with numerical models reproducing large-scale structures and dynamics [76].

Despite these advances, critical questions that must be addressed include: (1) How is Neptune's anomalous magnetic field generated? What is the nature of its dynamo process, and how does it affect magnetospheric dynamics? (2) What are the dynamical processes governing Neptune's magnetosphere, and how does it evolve over time? How do the solar wind and rotation shape magnetospheric dynamics and evolution? (3) What are the sources, transport pathways, and loss processes of magnetospheric plasma?

3.3.4. Neptune ionosphere

Neptune's ionosphere forms a critical interface between its neutral atmosphere and unique magnetosphere, serving as a key source of mass, momentum, and energy. Voyager 2 radio occultation data revealed a deep ionosphere extending at least 5000 km above the 10^5 Pa level, with a ~1800 km plasma scale height (~950 K for H^+-dominated plasma) [64]. While solar photoionization ionizes the upper ionosphere, Galactic Cosmic Rays dominate ionization at deeper levels (pressures up to 10^4 Pa), producing electron densities reaching 5×10^8 m^{-3}, far below the solar radiation-driven region [77]. The ionosphere and magnetosphere are bidirectionally coupled: intense auroral radio emissions suggest energetic particle precipitation [9], while H^+ outflow via polar wind or auroral acceleration may supply plasma comparable to that from Triton's neutral torus [68]. This torus is thought to originate from thermal escape of H, H_2, and N from Triton's atmosphere, which subsequently becomes ionized to serve as a plasma source [68]. However, this coupling remains poorly constrained.

Key unresolved questions include: (1) What are the characteristics (e.g., vertical structure and dominant ion composition) of Neptune's ionosphere? (2) How does the ionosphere couple with the magnetosphere?

3.4. Triton as a captured Kuiper Belt object: implications for comparative planetology

Beyond the three primary science themes outlined above, Triton also stands out due to its origin as a captured KBO. Its retrograde, highly inclined orbit provides compelling evidence that Triton is a dwarf planet captured from the primordial Kuiper Belt, likely acquired during the early Solar System via dissociation of a primordial binary during a close encounter with Neptune [6].

Triton shares key attributes with Pluto, including comparable size and a tenuous N_2-dominated atmosphere in vapor pressure equilibrium with surface ices [60,78]. However, unlike Pluto, Triton has undergone extensive tidal heating and orbital circularization following its capture, providing a unique window into evolutionary scenarios for a dwarf planet tidally activated by a giant planet [6,7]. Although over 100 dwarf planets with diameters exceeding 400 km are found in the Kuiper Belt, their extreme heliocentric distances render detailed observation or in situ exploration currently infeasible [8]. In contrast, Triton, as a dwarf planet orbiting a giant planet, is the most accessible KBO for high-resolution investigation via spacecraft flybys or orbital missions. Comprehensive measurements of its potential subsurface ocean, the extent of interior-surface-atmosphere coupling, and space environment directly inform the intrinsic properties of the primordial outer Solar System.

Comparative planetology between Triton, Pluto, and other KBOs thus forms a foundational framework for understanding the formation and evolution of the outer Solar System. Key scientific questions that must be addressed include: (1) How do Triton's internal structure, geology, and surface composition compare with those of Pluto and other KBOs, and how has capture processing shaped its primordial state? (2) What do these comparisons reveal about the compositional diversity and evolution of large bodies in the Kuiper Belt and the broader outer Solar System?

4. Mission architecture

The science return from an icy satellite mission is fundamentally determined by its architectural design. A tiered exploration strategy progressing from multiple flybys to orbital insertion and, ultimately, surface landing enables increasingly rigorous tests of key hypotheses regarding Triton's internal structure, subsurface ocean, space environment, and potential habitability. Below, we evaluate three representative architectures in order of increasing complexity and scientific capability.

(1) Neptune orbiter with multiple Triton flybys

This baseline architecture enables addressing core questions such as the confirmation of a subsurface ocean by high-sensitivity magnetometers along with plasma and electric field instruments to accurately measure the induction signal. High-resolution imaging and spectrometry permit near-global mapping of geology, volatile ices, and active plumes. Temporal monitoring of surface changes and magnetospheric interactions is also feasible. However, the transient flyby nature precludes precise gravity field and long-term deformation measurements of dynamic phenomena, limiting constraints on the characterization of Triton.

(2) Neptune orbiter followed by Triton orbit insertion

The two-phase architecture first characterizes the Neptune system before executing a dedicated transfer into Triton's orbit. Orbital operations enable continuous gravity and topography measurements that tightly constrain internal structure. Long-duration imaging allows monitoring of volatile transport and plume recurrence. The mission will obtain more detailed and comprehensive measurements of Triton's surrounding environment, especially its atmosphere, ionosphere, and their coupling with Neptune's magnetosphere.

(3) Triton orbiter with lander

The highest-tier architecture with a lander enables definitive in situ science. The lander can directly analyze surface and shallow subsurface materials for organic compounds, salts, and potential biosignatures. A seismometer can be deployed to probe the ice shell and detect endogenic activity. Seismology, proven by missions like InSight and the upcoming Dragonfly [35,79], offers the most direct and unambiguous method for constraining internal structure, including the existence of a subsurface ocean, ice shell thickness and deformation, and seafloor or interior tectonic activity. Advanced miniaturized, low-power seismometers now make this feasible with reduced mass, power, and operational complexity [80]. Additionally, accurate determination of Triton's atmospheric composition and isotopic ratios requires both an entry probe for vertical in situ profiles and orbital remote sensing using imaging spectrometers.

While a mission architecture combining orbital or multiple-flyby phases with a dedicated lander is scientifically compelling, achieving orbit around Neptune (requiring significant fuel or aerobraking) and especially around Triton poses severe engineering challenges, as highlighted in trajectory designs for missions like Odyssey and Trident [8,50].

5. Summary and perspectives

Ocean worlds beneath the surface of icy satellites represent among the most promising targets in the search for extraterrestrial habitability and potential biosignatures. Among known icy worlds, Triton stands out due to its unique combination of three characteristics: it is a primordial remnant from the outer Solar System, a candidate ocean world, and a geologically active satellite. These attributes make Triton a high-priority target for planetary science and astrobiology, particularly for investigations into the existence, nature, and potential habitability of its subsurface ocean.

This article reviews the scientific rationale and key questions guiding future missions to these ocean worlds, using Triton as an archetype for understanding the nature, evolution, and habitability of such systems. A mission to this icy satellite is inherently linked with the exploration of its host planetary system. As a result, the key scientific questions for Triton can be organized into three overarching themes: Subsurface Ocean and Habitability, Extent of Interior-Surface-Atmosphere Coupling, and Dynamic Space Environment. Future mission architectures, including orbital trajectories and payload suites, should be designed around these core objectives.

Key conclusions and strategic recommendations for future exploration of icy satellites are summarized as follows:

(1) Confirming the existence and characterizing the properties of Triton's subsurface ocean constitute the highest priority science objectives for future missions, as they are essential to assessing Triton's potential habitability. The electromagnetic method (see Section 3.3.2) requires high-sensitivity magnetometers along with plasma and electric field instruments to accurately measure the induction signal. In addition, gravity and tidal deformation measurements can constrain the depth and thickness of the subsurface ocean. A landed seismometer can directly probe the structure.

(2) Assessing potential habitability is a primary objective of Triton exploration. Among the key properties to investigate are the availability of bio-essential chemical ingredients and potential energy sources. If active plumes are detected during the mission, flyby trajectories that pass near them at a safe altitude could enable high-resolution neutral and ion mass spectrometers to detect volatiles and organic species that may originate from a subsurface ocean. Isotopic ratio measurements may further distinguish between biotic and abiotic signatures. Spectroscopic instruments aboard an orbiter or lander can identify surface signatures of salts, minerals, and organic compounds, which may originate from cryovolcanic activity. Additionally, a seismometer on a lander could detect tectonic or deformation events associated with icy subduction or seafloor tectonics, processes that may transport oxidants and nutrients from the surface or interior to the subsurface ocean. Together, these measurements provide critical constraints for evaluating Triton's potential habitability.

(3) A comprehensive investigation of Triton's atmosphere necessitates a synergistic approach combining in situ and remote sensing techniques. Remote sensing, particularly through imaging spectrometers, enables broad spatial mapping of atmospheric composition and structure. In contrast, in situ measurements, optimally obtained via an atmospheric entry probe, can provide high-resolution vertical profiles of key parameters. Such a probe should be equipped with dedicated pressure and temperature sensors, as well as a mass spectrometer, to accurately determine atmospheric composition and isotopic ratios.

(4) Space environment detection requires instrumentation capable of resolving multiple ion and electron species across a broad energy range. The development of multi-probe, multi-energy retarding potential analyzers would enable comprehensive plasma diagnostics, which are critical for characterizing local plasma populations and associated current systems.

(5) Overall, future missions to Triton should integrate in situ measurements and remote sensing to enable comprehensive, cross-validated studies of physical fields, charged particles, surface morphology, and composition. A systematic and stepwise strategy requires interdisciplinary collaboration across planetary science, space physics, geophysics, and astrobiology, enabled by advanced data fusion, forward modeling, inversion techniques, and trajectory design.

CRediT authorship contribution statement

Chi Wang: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Hui Li:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Yuxian Wang:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation. **Jiansen He:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Jihua Hao:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Ranran Liu:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Jiaqi Li:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Bingkun Yu:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Hui Huang:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Weiyi Zheng:** Writing – review & editing, Writing – original draft, Validation, Investigation.

Declaration of competing interest

Bingkun Yu is Guest Editors for this journal and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no conflicts of interest in this work.

Acknowledgments

This work was supported by the Pre-research Project on Civil Aerospace Technologies D010301 and D010202 funded by the China National Space Administration (CNSA), National Natural Science Foundation of China (42374198, 42188101). J.L. acknowledges the National

Key R&D Program of China (2024YFF0809900), and the National Natural Science Foundation of China (42474226, 42441827). R.L. acknowledges the National Natural Science Foundation of China (42322506).

References

[1] A.R. Hendrix, T.A. Hurford, L.M. Barge, et al., The NASA roadmap to ocean worlds, Astrobiology 19 (2019) 1–27.
[2] X. Chen, K. Li, J. Hao, Conception on the habitability exploration missions of the icy moon, Chin. Space Sci. Technol. 45 (2025) 175–184.
[3] Z. Hou, J. Liu, Y. Wang, et al., Exploration of extraterrestrial biosignatures and planetary habitability: a prospect, Fundam. Res. 6 (5) (2026) 2781–2791.
[4] Y. Wang, B. Yu, L. Geng, et al., Scientific themes in Venus exploration, Fundam. Res. (2026), doi:10.1016/j.fmre.2026.08.004.
[5] F. Nimmo, R.T. Pappalardo, Ocean worlds in the outer Solar System, J. Geophys. Res. Planets. 121 (2016) 1378–1399.
[6] C.B. Agnor, D.P. Hamilton, Neptune's capture of its moon Triton in a binary-planet gravitational encounter, Nature 441 (2006) 192–194.
[7] C. Wang, H. Li, D. Kong, et al., Cutting-edge scientific issues in ice giant exploration, Chin. Space Sci. Technol. 45 (2025) 1–11.
[8] A.M. Rymer, K.D. Runyon, B. Clyde, et al., Neptune Odyssey: a flagship concept for the exploration of the Neptune-Triton System, Planet. Sci. J. 2 (2021) 184.
[9] L.N. Fletcher, R. Helled, E. Roussos, et al., Ice Giant Systems: the scientific potential of orbital missions to Uranus and Neptune, Planet Space Sci. 191 (2020) 105030.
[10] C.C. Porco, P. Helfenstein, P.C. Thomas, et al., Cassini observes the active south pole of Enceladus, Science 311 (2006) 1393–1401.
[11] F. Postberg, Y. Sekine, F. Klenner, et al., Detection of phosphates originating from Enceladus's ocean, Nature 618 (2023) 489–493.
[12] H.W. Hsu, F. Postberg, Y. Sekine, et al., Ongoing hydrothermal activities within Enceladus, Nature 519 (2015) 207–210.
[13] National Academies of Sciences, Engineering, and Medicine, in: Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology, The National Academies Press, Washington, DC, 2023, pp. 2023–2032.
[14] S.M. MacKenzie, M. Neveu, A.F. Davila, et al., The Enceladus Orbilander mission concept: balancing return and resources in the search for life, Planet. Sci. J. 2 (2021) 77.
[15] J. Helbert, T.M. Bründl, M. Haag, et al., The mission to Enceladus—the ESA L4 mission, EPSC-DPS Joint Meeting 2025, 2025 EPSC-DPS2025-1307.
[16] R.T. Pappalardo, M.J.S. Belton, H.H. Breneman, et al., Does Europa have a subsurface ocean? Evaluation of the geological evidence, J. Geophys. Res. Planets 104 (1999) 24015–24055.
[17] M.G. Kivelson, K.K. Khurana, C.T. Russell, et al., Galileo magnetometer measurements: a stronger case for a subsurface ocean at Europa, Science 289 (2000) 1340–1343.
[18] X. Jia, M.G. Kivelson, K.K. Khurana, et al., Evidence of a plume on Europa from Galileo magnetic and plasma wave signatures, Nat. Astron. 2 (2018) 459–464.
[19] G.L. Villanueva, H.B. Hammel, S.N. Milam, et al., Endogenous CO2 ice mixture on the surface of Europa and no detection of plume activity, Science 381 (2023) 1305–1308.
[20] L.M. Prockter, R.T. Pappalardo, Folds on Europa: implications for crustal cycling and accommodation of extension, Science 289 (2000) 941–943.
[21] W.M. Grundy, B.J. Buratti, A.F. Cheng, et al., New Horizons mapping of Europa and Ganymede, Science 318 (2007) 234–237.
[22] R.W. Ebert, F. Allegrini, J.R. Szalay, et al., Plasma and magnetic field properties in Europa's wake from Juno, J. Geophys. Res. Space Phys. 130 (2025) e2024JA032520.
[23] L. Roth, J. Saur, K.D. Retherford, et al., Transient water vapor at Europa's South Pole, Science 343 (2014) 171–174.
[24] L.A. Cangahuala, S. Campagnola, B.K. Bradley, et al., Europa Clipper Mission design, mission plan, and navigation, Space Sci. Rev. 221 (2025) 22.
[25] A. Masters, R. Modolo, E. Roussos, et al., Magnetosphere and plasma science with the Jupiter Icy Moons explorer, Space Sci. Rev. 221 (2025) 24.
[26] F. Tosi, T. Roatsch, A. Galli, et al., Characterization of the surfaces and near-surface atmospheres of Ganymede, Europa and Callisto by JUICE, Space Sci. Rev. 220 (2024) 59.
[27] R.E. Samuelson, R.A. Hanel, V.G. Kunde, et al., Mean molecular weight and hydrogen abundance of Titan's atmosphere, Nature 292 (1981) 688–693.
[28] V.G. Kunde, A.C. Aikin, R.A. Hanel, et al., C4H2, HC3N and C2N2 in Titan's atmosphere, Nature 292 (1981) 686–688.
[29] J.P. Lebreton, O. Witasse, C. Sollazzo, et al., An overview of the descent and landing of the Huygens probe on Titan, Nature 438 (2005) 758–764.
[30] L. Iess, N.J. Rappaport, R.A. Jacobson, et al., Gravity field, shape, and moment of inertia of Titan, Science 327 (2010) 1367–1369.
[31] R.M. Baland, T. Van Hoolst, M. Yseboodt, et al., Titan's obliquity as evidence of a subsurface ocean? Astronom. Astrophys. 530 (2011) A141.
[32] F. Petricca, S.D. Vance, M. Parisi, et al., Titan's strong tidal dissipation precludes a subsurface ocean, Nature 648 (2025) 556–561.
[33] J. Cui, R.V. Yelle, V. Vuitton, et al., Analysis of Titan's neutral upper atmosphere from Cassini Ion Neutral Mass Spectrometer measurements, Icarus 200 (2009) 581–615.
[34] S. Rodriguez, S. Le Mouélic, P. Rannou, et al., Global circulation as the main source of cloud activity on Titan, Nature 459 (2009) 678–682.
[35] R.D. Lorenz, E.P. Turtle, J.W. Barnes, et al., Dragonfly: a rotorcraft lander concept for scientific exploration at Titan, Johns Hopkins APL Tech. Dig. 34 (2018) 14.
[36] B.A. Smith, L.A. Soderblom, R. Beebe, et al., The Galilean Satellites and Jupiter: voyager 2 imaging science results, Science 206 (1979) 927–950.
[37] M.G. Kivelson, K.K. Khurana, M. Volwerk, The permanent and inductive magnetic moments of Ganymede, Icarus 157 (2002) 507–522.
[38] J. Saur, S. Duling, L. Roth, et al., The search for a subsurface ocean in Ganymede with Hubble Space Telescope observations of its auroral ovals, J. Geophys. Res. Space Phys. 120 (2015) 1715–1737.
[39] C. Zimmer, Subsurface oceans on Europa and Callisto: constraints from Galileo magnetometer observations, Icarus 147 (2000) 329–347.
[40] O. Hartkorn, J. Saur, Induction signals from Callisto's ionosphere and their implications on a possible subsurface ocean, J. Geophys. Res.: Space Phys. 122 (2017) 11677–11697.
[41] C.J. Cochrane, S.D. Vance, J.C. Castillo-Rogez, Stronger evidence of a subsurface ocean within Callisto from a multifrequency investigation of its induced magnetic field, AGU Adv. 6 (2025) e2024AV001237.
[42] J. Anderson, Shape, mean radius, gravity field, and interior structure of Callisto, Icarus 153 (2001) 157–161.
[43] R.M. Canup, W.R. Ward, Formation of the galilean satellites: conditions of accretion, Astron. J. (N. Y.) 124 (2002) (2002) 3404–3423.
[44] P. Gao, D.J. Stevenson, Nonhydrostatic effects and the determination of icy satellites' moment of inertia, Icarus 226 (2013) 1185–1191.
[45] D. Bhattacharyya, J.T. Clarke, J. Montgomery, et al., Evidence for auroral emissions from Callisto's footprint in HST UV images, J. Geophys. Res. Space Phys. 123 (2018) 364–373.
[46] J. Rabia, V. Hue, C.K. Louis, et al., In situ and remote observations of the ultraviolet footprint of the moon Callisto by the Juno spacecraft, Nat. Commun. 16 (2025) 7791.
[47] B.A. Smith, L.A. Soderblom, D. Banfield, et al., Voyager 2 at Neptune: imaging science results, Science 246 (1989) 1422–1449.
[48] J.D. Hofgartner, S.P.D. Birch, J. Castillo, et al., Hypotheses for Triton's plumes: new analyses and future remote sensing tests, Icarus 375 (2022) 114835.
[49] F. Nimmo, J.R. Spencer, Powering Triton's recent geological activity by obliquity tides: implications for Pluto geology, Icarus 246 (2015) 2–10.
[50] W. Frazier, D. Bearden, K.L. Mitchell, et al., Trident: the path to Triton on a discovery budget, in: 2020 IEEE Aerospace Conference, 2020, pp. 1–12.
[51] D. Turrini, R. Politi, R. Peron, et al., The comparative exploration of the ice giant planets with twin spacecraft: unveiling the history of our Solar System, Planet Space Sci. 104 (2014) 93–107.
[52] F. Nimmo, C. Bierson, W.B. McKinnon, Pluto and triton: interior structures, lithospheres and potential for oceans, in: A. Luspay-Kuti, K. Mandt (Eds.), Triton and Pluto, Institute of Physics Publishing (IOP Publishing), 2025, pp. 1–31.
[53] P. Schenk, C. Beddingfield, T. Bertrand, et al., Triton: Topography and geology of a probable ocean world with comparison to Pluto and Charon, Remote Sensing 13 (2021) 3476.
[54] K. Ohno, X. Zhang, R. Tazaki, et al., Haze formation on Triton, Astrophys. J. 912 (2021) 37.
[55] M. Burgdorf, D.P. Cruikshank, C.M. Dalle Ore, et al., A tentative identification of HCN ice on triton, Astrophys. J. Lett. 718 (2010) L53–L57.
[56] B.J. Holler, L.A. Young, W.M. Grundy, et al., On the surface composition of Triton's southern latitudes, Icarus 267 (2016) 255–266.
[57] I. Wong, D. Hines, R. Brunetto, et al., The complex surface and atmospheric properties of Triton revealed by JWST/NIRSpec, Bull. AAS 55 (2023) 8.
[58] P. Schenk, M.P.A. Jackson, Diapirism on Triton: a record of crustal layering and instability, Geology 21 (1993) 299.
[59] L.M. Prockter, F. Nimmo, R.T. Pappalardo, A shear heating origin for ridges on Triton, Geophys. Res. Lett. 32 (2005) 2005GL022832.
[60] A.L. Broadfoot, S.K. Atreya, J.L. Bertaux, et al., Ultraviolet spectrometer observations of Neptune and Triton, Science 246 (1989) 1459–1466.
[61] L.A. Soderblom, S.W. Kieffer, T.L. Becker, et al., Triton's geyser-like plumes: discovery and basic characterization, Science 250 (1990) 410–415.
[62] C.J. Hansen, A.S. McEwen, A.P. Ingersoll, et al., Surface and airborne evidence for plumes and winds on Triton, Science 250 (1990) 421–424.
[63] E. Lellouch, C. De Bergh, B. Sicardy, et al., Detection of CO in Triton's atmosphere and the nature of surface-atmosphere interactions, Astron. Astrophys. 512 (2010) L8.
[64] G.L. Tyler, D.N. Sweetnam, J.D. Anderson, et al., Voyager radio science observations of Neptune and Triton, Science 246 (1989) 1466–1473.
[65] H. Gu, J. Cui, D.D. Niu, et al., Non-thermal escape on Triton driven by atmospheric and ionospheric chemistry, Astron. Astrophys. 650 (2021) A130.
[66] B. Benne, B. Benmahi, M. Dobrijevic, et al., Impact of the transport of magnetospheric electrons on the composition of the Triton atmosphere, Astron. Astrophys. 686 (2024) A22.
[67] H. Lammer, Mass loss of N2 molecules from Triton by magnetospheric plasma interaction, Planet Space Sci. 43 (1995) 845–850.
[68] C. Paty, C.S. Arridge, I.J. Cohen, et al., Ice giant magnetospheres, Phil. Trans. Royal Soc. A 378 (2020) 20190480.
[69] J.S. He, C.P. Hou, J.Q. Li, et al., Probing Triton's space environment and internal structure: an integrated detection-inversion concept, Fundam. Res. (2025) this issue.
[70] K.K. Khurana, J. Liu, J. Castillo, et al., Dual-frequency electromagnetic sounding of a Triton ocean from a single flyby, Phil. Trans. R. Soc. A 382 (2024) 20240087.
[71] K.K. Khurana, M.G. Kivelson, C.T. Russell, Searching for liquid water in Europa by using surface observatories, Astrobiology 2 (2002) 93–103.
[72] S.C. Stähler, M.P. Panning, S.D. Vance, et al., Seismic wave propagation in icy ocean worlds, J. Geophys. Res. Planets 123 (2018) 206–232.
[73] C.J. Cochrane, R.R. Persinger, S.D. Vance, et al., Single- and multi-pass magnetometric subsurface ocean detection and characterization in icy worlds using prin-

cipal component analysis (PCA): application to triton, Earth Space Sci. 9 (2022) e2021EA002034.
[74] C.S. Arridge, C. Paty, Asymmetrical magnetospheres: Uranus and Neptune, in: R. Maggiolo, N. André, H. Hasegawa, et al. (Eds.), Magnetospheres in the Solar System, Wiley, 2021, pp. 515–534.
[75] H. Melin, L. Moore, L.N. Fletcher, et al., Discovery of H3+ and infrared aurorae at Neptune with JWST, Nat. Astron. 9 (2025) 666–671.
[76] L. Mejnertsen, J.P. Eastwood, J.P. Chittenden, et al., Global MHD simulations of Neptune's magnetosphere, J. Geophys. Res. Space Phys. 121 (2016) 7497–7513.
[77] G.J. Molina-Cuberos, O. Witasse, D. Toledo, et al., The low-altitude ionosphere of the ice giant planets, J. Geophys. Res. Planets. 128 (2023) e2022JE007568.
[78] S.A. Stern, W.M. Grundy, W.B. McKinnon, et al., The Pluto system after new horizons, Annu. Rev. Astron. Astrophys. 56 (2018) 357–392.
[79] W.B. Banerdt, S.E. Smrekar, D. Banfield, et al., Initial results from the InSight mission on Mars, Nat. Geosci. 13 (2020) 183–189.
[80] S.C. Stähler, M. Knapmeyer, Seismology in the solar system, in: C. Schmelzbach, S.C. Stähler (Eds.), Geophysical Exploration of the Solar System, Advances in Geophysics, Elsevier, 2022, pp. 9–64.

Author profile

Chi Wang (BRID: 09108.00.39752) is an academician of Chinese Academy of Sciences (CAS) and Director General of National Space Science Center, CAS. He received his PhD from the Massachusetts Institute of Technology. He is in charge of the Strategic Priority Program on Space Science (Phase II), Co-PI of the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) mission, and Chief Commander of the Chinese Meridian Project (phase II). He is the Deputy Chief Engineer of Chang'e 4 mission of Chinese Lunar Exploration Program and is in charge of the payloads system of Chang'e 4, Chang'e 5 and Tianwen-1 Mars mission.

Hui Li (BRID: 03087.00.32579) is a professor and Deputy Director General of National Space Science Center, Chinese Academy of Sciences. He received his PhD from University of Chinese Academy of Sciences in 2011. He has led more than 10 national-level research projects and was selected as one of the China-U.S. Space Science Young Leaders. He currently serves as a council member of the Chinese Space Science Society, vice chair of the Planetary Physics Committee of the Chinese Geophysical Society, co-convener of the science team for the Tianwen-2 mission, member of the planetary science expert group for lunar and deep-space exploration.