

Research Article

From Ice to Life: The Scientific Case for Europa's Habitability

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Abstract

Europa, one of Jupiter's Galilean satellites, is a key astrobiological target due to compelling evidence for a global subsurface ocean beneath an estimated 15-25 km thick ice shell. Tidal dissipation, driven by Europa's orbital eccentricity and gravitational interactions with Io and Ganymede, provides sufficient internal heating to sustain liquid water. Geological features such as chaos terrains, ridged plains, and cycloidal fractures indicate a geologically young and active surface, likely shaped by endogenic processes including cryovolcanism and ice shell convection. These mechanisms may facilitate the exchange of subsurface materials, such as water, ammonia, and methane, with the surface, where they rapidly freeze. Spectroscopic data from the Galileo mission and ground-based observations reveal a chemically diverse surface enriched in hydrated salts, sulfuric acid hydrates, and possible organic compounds, with contributions from both internal activity and exogenic exchange with Io's sulfur-rich environment. Europa's tenuous, oxygen-dominated exosphere, maintained by radiolysis of surface ice, further supports active surface-atmosphere interactions. Taken together, current geophysical, chemical, and geological evidence suggests Europa satisfies three key conditions for habitability: the presence of liquid water, available redox energy, and essential prebiotic chemistry. This paper synthesizes current knowledge of Europa's formation, internal structure, thermal evolution, surface composition, and exospheric processes. It also outlines the science objectives of NASA's Europa Clipper and ESA's JUICE missions, which aim to characterize Europa's Ocean, constrain ice shell thickness, and evaluate its habitability. These missions will play a critical role in advancing our understanding of icy ocean worlds and the potential for life beyond Earth.

Keywords

Europa, Planetary Science, Habitable Zone

1. Introduction

Europa, the fourth-largest of Jupiter's moons and one of the Galilean satellites, has a mean diameter of approximately 3,121.6 km, making it slightly smaller than Earth's Moon (3,474.8 km) [1]. Despite orbiting Jupiter at a distance of ~671,000 km and residing ~5.2 astronomical units (AU) from the Sun, Europa exhibits a suite of geophysical and astrobio-

logical characteristics that make it a prime target for the search for extraterrestrial life in the Solar System [35, 36, 15].

The moon's internal energy budget is dominated by tidal heating, resulting from orbital eccentricity and resonance interactions with Io and Ganymede. This gravitational forcing induces periodic deformation of Europa's interior, dissipating

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energy as heat [37]. Modeling of this process supports the existence of a global subsurface ocean beneath an ice shell estimated to be 15-25 km thick, with the ocean itself potentially exceeding 100 km in depth [21, 16]. The ocean's contact with a silicate-rich mantle may allow for hydrothermal circulation, facilitating water-rock interactions that can generate redox gradients capable of sustaining chemosynthetic life in which the biological conversion of carbon-containing molecules and nutrients into simple organic matter [50, 6].

Europa's surface is among the smoothest and geologically youngest in the Solar System, with a surface age estimated at 40-90 million years [54]. It displays relatively few impact craters, instead dominated by extensive networks of double ridges, chaos terrain, lenticulae, and other features indicative of ongoing or recent resurfacing [8, 42]. These morphological features are interpreted as evidence for endogenic activity, including diapirism, tectonism, and possible cryovolcanism, which could facilitate the vertical transport of materials between the surface and subsurface ocean [35].

Spectroscopic observations from Galileo's Near-Infrared Mapping Spectrometer (NIMS), along with Earth-based and Hubble Space Telescope campaigns, have revealed a chemically diverse and spatially heterogeneous surface composition [24, 4, 49]. Detected compounds include hydrated sulfate and chloride salts, sulfuric acid hydrates, and potential organics, which may be linked to subsurface oceanic upwelling, radiolytic surface alteration, or both [7, 13]. These findings imply that Europa's surface is chemically coupled with its interior, and potentially with the ocean, in a manner analogous to terrestrial oceanic upwelling systems that stimulate biogeochemical cycling and nutrient transport [51].

Collectively, the integration of geophysical, geological, and spectroscopic evidence positions Europa as a high-priority astrobiological target. The presence of a persistent subsurface ocean, an active icy shell, and energy sources capable of sustaining chemical disequilibria supports the possibility of habitability [14, 52]. Forthcoming missions, including NASA's Europa Clipper and ESA's Jupiter Icy Moons Explorer (JUICE), aim to characterize Europa's subsurface structure, surface composition, and potential biosignatures through high-resolution imaging, magnetometry, radar sounding, and in situ spectrometry [9, 38]. These investigations are poised to substantially advance our understanding of Europa's potential to support life and its role in the broader context of planetary habitability.

2. Orbital Dynamics and Tidal Heating

Tidal heating on Europa is primarily driven by the intense gravitational forces exerted by Jupiter, which cause the moon to stretch as it orbits the planet [47] (Figure 1). This effect is amplified by Europa's slightly elliptical orbit (Figure 1), which is maintained by its gravitational interactions with neighboring moons, Io and Ganymede, through a Laplace resonance (occurs when orbiting bodies exert regular, peri-

odic gravitational influence on each other). In this resonance ratios 4:2:1, it means that every orbit Ganymede completes, Europa orbits twice and Io four times, preventing Europa's orbit from becoming circular and ensuring continued tidal stress [10]. As Europa travels along this elliptical path, it experiences varying gravitational pulls, causing its interior to stretch and contract repeatedly. This mechanical flexing generates internal friction, which is then converted into heat, a process known as tidal heating [17]. The generated heat is believed to be sufficient to maintain a subsurface ocean beneath Europa's icy crust, despite surface temperatures averaging around -160°C [36]. This hidden ocean, sustained by tidal forces, makes Europa a compelling target in the search for extraterrestrial life.

The tidal stresses not only warm Europa's interior but also fracture its icy shell, leading to observable surface features such as ridges, cracks, and possibly plumes (Figure 3). Tidal dissipation may be especially intense near the base of the ice shell or at the ocean floor, providing the energy necessary to sustain hydrothermal activity, which is the key to supporting potential microbial life [11].

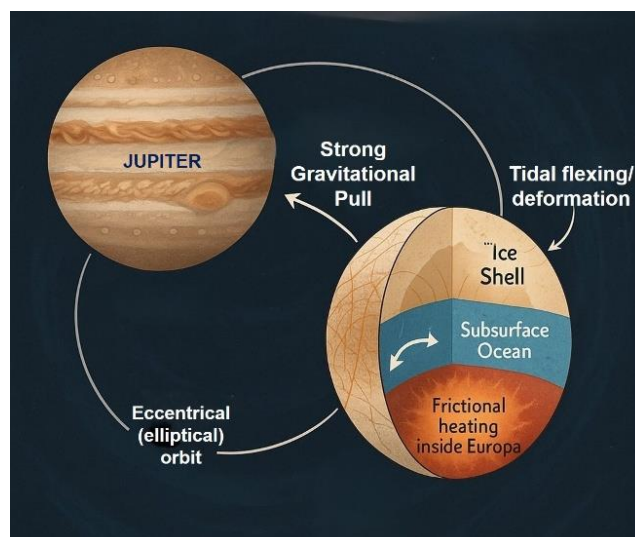


Figure 1. Diagram illustrating the tidal heating mechanism in Europa, where Jupiter's strong gravitational pull and Europa's elliptical orbit cause tidal flexing, generating frictional heat that may sustain a subsurface ocean (modified from [31] Illustration).

3. Formation and Internal Structure

Europa is believed to have formed within the circum-Jovian subnebula, a gaseous disk of material that surrounded Jupiter during its final stages of accretion. The thermal and compositional conditions within this disk likely facilitated Europa's early differentiation into a stratified internal structure consisting of an iron-rich core, a silicate mantle, and an overlying ice-water shell.

Geophysical data acquired by the Galileo spacecraft have provided strong constraints on Europa's internal configura-

tion. Gravity field measurements, in conjunction with magnetic induction signatures, suggest the presence of a global, subsurface liquid water ocean situated beneath an outer ice shell. The thickness of the ice shell is estimated to range from approximately 15 to 25 kilometers, overlaying a liquid layer of water and/or brine that may be 60 to 150 kilometers in depth [21]. These observations are further supported by the induced magnetic field data, which imply the presence of a conductive layer consistent with a saline ocean.

Interior structural models, informed by moment of inertia constraints and thermal evolution simulations, suggest that Europa possesses a metallic core with an estimated radius of ~500 kilometers, surrounded by a silicate mantle (Figure 2). Overlying this rocky interior is a water-rich shell, composed of both liquid and solid phases of H₂O (Figure 2). The heat necessary to sustain a subsurface ocean is supplied by a combination of long-lived radiogenic isotopes in the silicate interior and tidal dissipation resulting from Europa's orbital eccentricity and its gravitational interactions with Jupiter and neighboring Galilean moons.

Scientists believe that beneath the icy surface of Jupiter's moon Europa lies a saltwater ocean that may hold more than twice the amount of liquid water found in all of Earth's oceans (Figure 3).

Due to the subsurface ocean is in direct contact with the silicate mantle (Figure 3), as suggested by several geophysical and thermodynamic models, water-rock interactions at the ocean-mantle interface may produce redox gradients and chemical disequilibria capable of sustaining potential prebiotic or biotic processes. In particular, serpentinization reactions involving ultramafic rocks may generate molecular hydrogen (H₂), methane (CH₄), and other reduced species, which could serve as energy sources for hypothetical chemotrophic ecosystems by converting inorganic carbon to organic compounds [51].

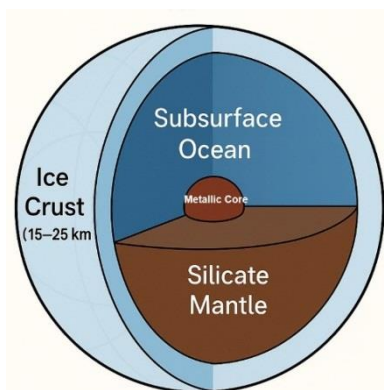


Figure 2. Schematic cross-section of Europa's internal structure showing a differentiated body with an outer ice shell, global subsurface ocean, silicate mantle, and metallic core (modified from [31] illustrations).

In the outer ice shell, thermal gradients likely drive sol-

id-state convection, which may promote diapiric upwelling and dynamic resurfacing processes observed in Europa's geologically young terrain. This convective circulation, coupled with episodic melting, could facilitate exchange between the surface and subsurface environments, further enhancing Europa's astrobiological potential.

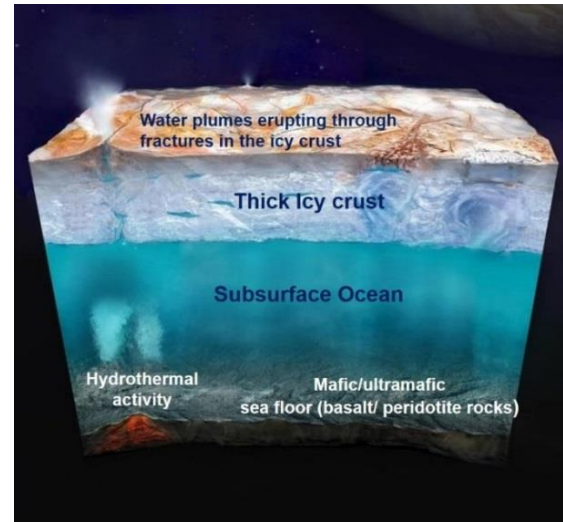


Figure 3. Artist's illustration of the interior structure of Jupiter's moon Europa, showing a thick icy crust (top), subsurface ocean (middle), and rocky mantle (bottom). The image illustrates features such as surface ridges, potential water plumes erupting from the ice shell, and hydrothermal activity on the ocean floor, supporting the possibility of a habitable environment beneath Europa's surface. (Modified from [34]).

4. Surface Geology and Morphology

Europa's surface is among the smoothest in the solar system, exhibiting a high albedo of approximately 0.60, primarily due to the presence of fresh water ice accumulation (Table 1). The Albedo scale can be calculated using the following equation;

$$\text{Albedo} = \frac{\text{Reflected Radiation}}{\text{Incoming Radiation}}$$

For example, if the ice surface reflects 80 watts per square meter of solar radiation and receives 100 watts per square meter, the albedo is $80/100 = 0.80$ or 80%. Table 1 represents the albedo range of common planetary materials.

The tectonic and cryovolcanic features are common and display a notable shortage of large impact craters, implying a geologically young age of less than 100 million years [54]. This relative youth suggests ongoing resurfacing processes likely driven by internal heat and interactions between the subsurface ocean and the overlying ice shell. Prominent geological structures include linear features (Figure 4), which are global-scale, dark, double ridges extending for hundreds of kilometers, believed to form through tensile fracturing and localized upwelling of warmer ice or brine. Chaos terrain (Figure 4)

consists of disrupted ice blocks set within a hummocky matrix, possibly resulting from partial melting beneath the shell and subsequent structural collapse. Ridges including hills and domes (Figure 4) are also common and are interpreted as evidence of localized cryovolcanism or convective upwelling currents; some domes may represent diapirs of warm ice or briny material ascending through the ice. These diverse surface features are broadly analogous to tectonic and volcanic processes on Earth and may serve as critical indicators of geologic exchange between the surface and the underlying ocean.

Table 1. Simplified albedo scale of common planetary materials [46].

Material	Albedo Range	Example Body or Surface
Clean Ice	0.80-0.90	Europa, Enceladus
Snow	0.70-0.90	Earth polar regions
Europa Surface Ice	~0.60	Europa
Sand	0.25-0.45	Deserts on Earth, Mars
Basalt	0.10-0.20	Lunar maria, Martian volcanics
Lunar Regolith	0.07-0.12	Moon highlands
Water	0.05-0.10	Earth’s oceans
Charcoal	~0.04	Very dark organic material

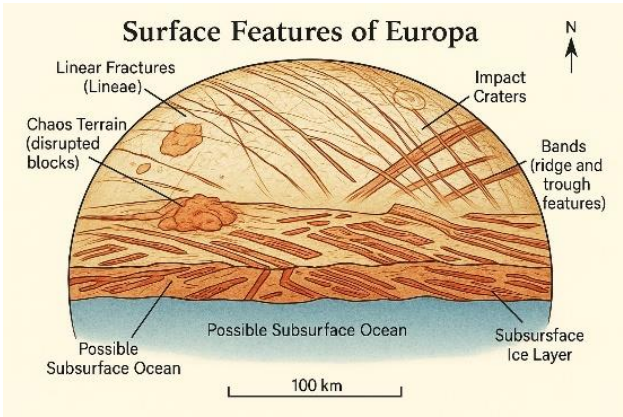


Figure 4. Surface of Europa showing major geologic such as linear features, chaos regions, and ridges. These features indicate active cryogeologic processes and surface activities [29].

5. Surface Chemistry and Spectroscopic Signatures

Observations of Europa’s surface using the Near-Infrared Mapping Spectrometer (NIMS) aboard the Galileo spacecraft (Figure 5) have provided compelling evidence for the presence of brines and salt grains mixed with water ice. These mixtures exhibit distinct spectral absorption features, notably

at 460 nm, 723 nm, and 830 nm (Figure 6), which are diagnostic of specific molecular or lattice vibrational modes. Such spectral signatures are essential for compositional interpretation from remote sensing data and for identifying surface materials on icy satellites [33].

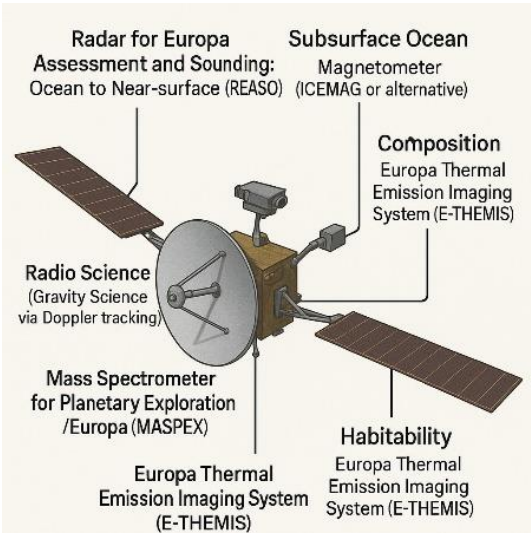


Figure 5. Image of Galileo spacecraft equipped with Europa Clipper's scientific instruments designed to study Europa's habitability and subsurface ocean (modified from [32]).

Laboratory spectra of equivalent materials including photolyzed hydrogen sulfide and water mixtures ($\text{H}_2\text{S} + 10 \text{H}_2\text{O}$), non-irradiated sodium chloride (NaCl) grains, hydrated magnesium sulfate ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), various brine solutions, and salt grains with and without additional water exhibit spectral behaviors consistent with those observed on Europa (Figure 6). The photolyzed $\text{H}_2\text{S} + 10 \text{H}_2\text{O}$ sample, which simulates radiolytic processing under ultraviolet irradiation, displays the highest overall reflectance across the studied spectral range (Figure 6), indicating strong scattering and minimal absorption. NaCl grains similarly exhibit high reflectance, while slightly lower than that of the photolyzed mixtures (Figure 6). In contrast, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ grains demonstrate markedly lower reflectance, consistent with darker and more absorbing surface materials (Figure 6).

The spectral observations support a surface composition dominated by crystalline H_2O ice, with additional contributions from hydrated sulfate salts, radiolytically processed sulfuric acid, and potentially organic compounds [25]. More recent laboratory simulations including ground and space based spectroscopic studies have highlighted the significance of irradiated NaCl in Europa’s surface mineralogy, particularly within geologically active regions such as Tara Regio [13]. Under Europa-like cryogenic and radiolytic conditions, NaCl is known to undergo alteration via electron and ion bombardment, resulting in characteristic optical absorption features [2, 41]. These features have been positively identified

in the Hubble Space Telescope (HST) spectra of Europa's surface [49], especially in areas associated with recent geological activity, where surface and subsurface material exchange is likely to occur. The discovery of radiolytically altered sodium chloride (NaCl), along with the weak or missing signals from sulfate compounds, has important implications for understanding the composition of Europa's subsurface ocean. Earlier theories proposed that magnesium and sodium sulfates were the main salts present. However, recent spectroscopic data suggest that Europa's Ocean may instead be rich in chlorides. This would make it more similar to Earth's salty oceans. Such findings help scientists better understand Europa's chemical history and increase interest in its potential to support life.

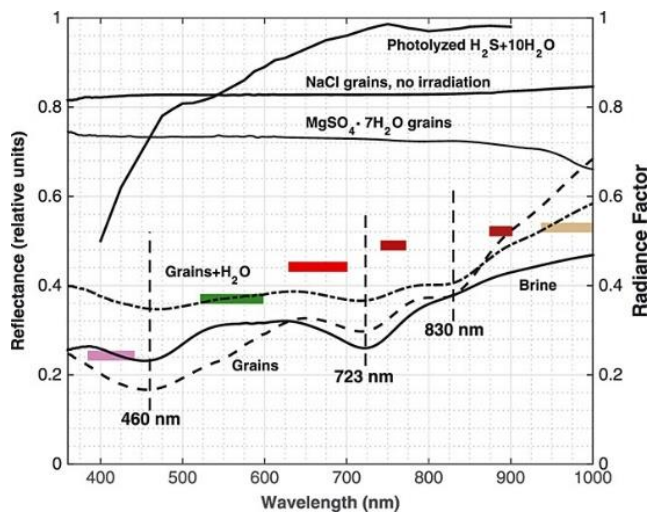


Figure 6. Spectral reflectance data showing various surface materials on Europa. X-axis represents wavelength of light in nanometers (nm). Left Y-axis represents the reflectance of light (0 = no reflection and 1 = all light reflected), Right Y-axis represents Radiance factor (a similar measure of brightness) [33].

6. Atmosphere and Exosphere

Europa possesses an exceedingly weak atmosphere (Figure 7), with a surface pressure estimated on the order of $\sim 10^{-12}$ bar, primarily composed of molecular oxygen (O_2) [12, 39]. The origin of this oxygen-rich atmosphere is attributed to radiolytic processes acting upon the moon's surface water ice. Energetic charged particles, principally electrons and ions originating from Jupiter's intense magnetospheric environment, continuously bombard Europa's icy surface, dissociating H_2O molecules into hydrogen and oxygen atoms [19]. The relatively low gravitational binding energy of Europa allows for the preferential escape of lighter hydrogen into space, while the heavier oxygen atoms are retained, accumulating to form a thin, gravitationally bound atmosphere [5].

Beyond the primary molecular oxygen component, Europa's extended exosphere includes a suite of additional neutral species. Observational data and modeling suggest the pres-

ence of atomic and molecular hydrogen (H , H_2), hydroxyl radicals (OH), and trace alkali metals such as sodium (Na) and potassium (K) [3, 22, 40].

Notably, ultraviolet spectroscopic observations by the Hubble Space Telescope have revealed transient water vapor plumes emanating from Europa's south polar region [44]. These observations suggest localized cryovolcanic activity or venting processes that may directly connect the surface to underlying liquid water reservoirs, likely housed within a global subsurface ocean [14, 18]. Such plume activity has significant implications for both the atmospheric composition and Europa's astrobiological potential, providing a mechanism for the vertical transport of subsurface material to altitudes accessible by remote sensing.

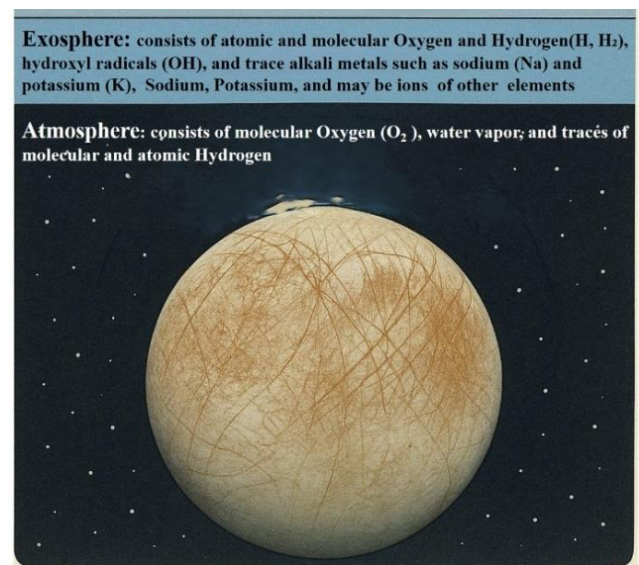


Figure 7. Schematic illustration of Europa's near-surface neutral gas environment. The moon's extremely weak atmosphere, primarily composed of O_2 produced by surface ice radiolysis, transitions into a collisionless exosphere at higher altitudes. Due to the low surface pressure ($\sim 10^{-12}$ bar), Europa lacks a well-defined stratified atmosphere (Artist's concept modified from information provided by [30]).

7. Magnetic Induction and Ocean Detection

Observations conducted by the Galileo spacecraft's onboard magnetometer have revealed anomalies in the local magnetic field environment during multiple flybys of Europa. These magnetic field signatures, characterized by periodic variations correlated with Europa's orbital position, have been interpreted as induced magnetic responses resulting from the interaction between Jupiter's time-variable magnetospheric field and a conducting layer within Europa's interior [20, 21].

The prevailing geophysical interpretation attributes these induction signals to the presence of a global subsurface ocean, situated beneath the outer ice shell, possessing sufficient

electrical conductivity to generate a secondary magnetic field in response to the primary Jovian field (Figure 8). Modeling of the observed induction response constrains the conductive layer to a depth of approximately 100 km below the surface, with a thickness of up to several tens of kilometers [55, 45].

To achieve the observed levels of magnetic response, the subsurface liquid must exhibit an electrical conductivity consistent with that of a saltwater solution. Thermochemical models, in conjunction with induction data, suggest that a salinity in the range of approximately 5-10% by weight, comparable to Earth's ocean, is sufficient to account for the measured induction amplitudes and phases [14, 52]. These results strongly support the hypothesis that Europa harbors a global subsurface ocean, likely maintained in a liquid state through a combination of tidal heating and radiogenic energy sources.

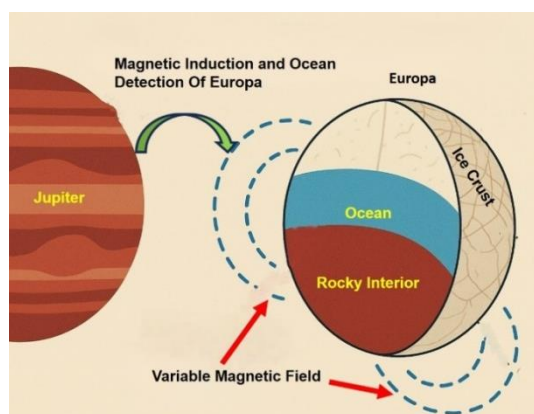


Figure 8. This schematic illustrates how Jupiter's time-varying magnetic field (blue dashed lines) induces a secondary magnetic field within Europa, indicating the presence of a conductive subsurface ocean beneath an icy crust. Europa's internal layers, ice crust, liquid water ocean, and rocky interior are shown in cross-section diagram. The detection of the induced magnetic field provides key evidence for the existence of Europa's global ocean (modified from [28]).

8. Astrobiological Potential and Prospective Investigations by Upcoming Missions

Europa satisfies all three key requirements for life as we know it: (1) liquid water, (2) chemical nutrients, and (3) an energy source. Evidence from spacecraft data and modeling supports the presence of a subsurface ocean beneath Europa's icy crust, whose composition and thermal characteristics suggest that these requirements may indeed be met. Past observations, including Europa's geologically young surface and induced magnetic field signatures, strongly indicate a global salty ocean heated by internal processes [43].

The relative favorability of redox reactions in marine sediments is governed by the Gibbs free energy change (ΔG) associated with each reaction. In illustrative diagram of figure

9, the start points of arrows represent the energy level of individual half-cell reactions (either oxidation or reduction), while the lengths of the arrows correspond to the estimated ΔG of the complete redox couple. Longer arrows indicate reactions that yield more free energy and are thus more thermodynamically favorable. This energy-based framework explains the depth-dependent sequence of terminal electron-accepting processes used by microbial communities in sedimentary environments where oxygen reduction is the most favorable and the methanogenesis is the least favorable (Figure 9) [23].

If hydrothermal activity is present at the seafloor, it could provide the same conditions that support life at Earth's deep-sea vents, independent of solar energy. On Earth, deep-sea hydrothermal systems host chemosynthetic organisms powered by redox gradients arising from interactions between reduced compounds (e.g., hydrogen or methane) and oxidants like sulfate or oxygen (Figure 9). Similar redox-driven chemistries could exist on Europa if heat and chemical flux from the rocky seafloor meet liquid water in contact with oxidants transported through the ice shell [48]. These environments may host chemosynthetic organisms fueled by redox gradients. On Earth, redox gradients, caused by variations in oxygen, chemical composition, and microbial activity are fundamental to life, enabling diverse metabolic pathways in environments from hydrothermal vents to subglacial lakes [53, 48].

NASA's Europa Clipper mission, launched in October 14, 2024, will conduct approximately 50 close flybys of Europa using a suite of advanced instruments, including ice-penetrating radar, mass spectrometers, magnetometers, plasma sensors, ultraviolet (UV) and thermal imagers, and a dust analyzer [26, 43, 27]. The main goal of the Europa Clipper mission is to investigate whether there are places below Europa's surface that could support life by gathering data to assess Europa's potential habitability.

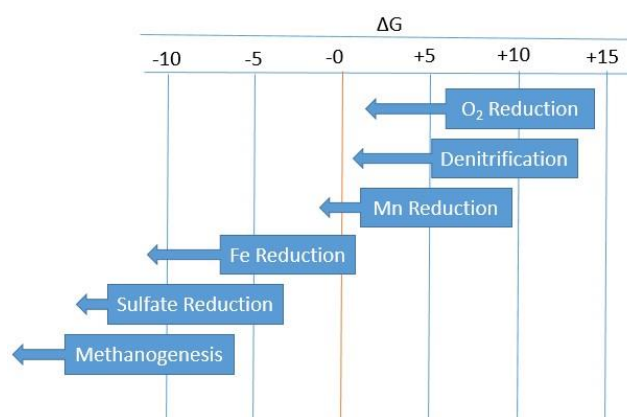


Figure 9. Relative favorability of redox reactions in marine sediments based on energy. Start points of arrows indicate energy associated with half-cell reaction. Lengths of arrows indicate an estimate of Gibb's free energy (ΔG) for the reaction where a higher ΔG is more energetically favorable [23].

9. Conclusions

Europa remains one of the most promising targets in the search for life beyond Earth, owing to strong evidence for a global subsurface ocean in contact with a rocky mantle. This configuration permits water-rock interactions that can generate energy gradients and synthesize biologically relevant compounds. Surface features such as ridges, chaos terrains, and possible plumes indicate active geologic processes that may facilitate exchange between the ocean and surface, enabling redox cycling critical for habitability.

Spectroscopic detections of hydrated salts and radiolytic products suggest a chemically diverse environment, while magnetic induction confirms a conductive, likely saline, internal ocean. The oxygen-rich atmosphere further reflects dynamic interactions between surface ice and Jupiter's radiation environment.

Upcoming missions, NASA's Europa Clipper and ESA's JUICE, will provide key data on Europa's ice shell, ocean properties, surface composition, and potential biosignatures. With the presence of liquid water, chemical energy, and essential elements, Europa is a prime candidate for astrobiological exploration and a natural laboratory for understanding the conditions necessary for life in the Solar System.

Abbreviations

NASA	the National Aeronautics and Space Administration
ESA	European Space Agency
AU	Astronomical Unit
NIMS	Near-Infrared Mapping Spectrometer
JUICE	JUpiter ICy moons Explorer

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Author Contributions

Mossbah Kolkas is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

Appendix

NASA's Europa Clipper: is a robotic spacecraft on a mission to study Jupiter's icy moon, Europa, to determine if it contains conditions suitable for life.

AU: (Astronomical Unit) a unit of length equal to the average distance between the Earth and the Sun, which is about 150 million Kilometers.

NASA/JPL-Caltech: signifies the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL), which is operated by the California Institute of Technology (Caltech).

Albedo: is the fraction of sunlight reflected by an object.

NASA/JPL-Caltech/SWRI: refers to an affiliation of the National Aeronautics and Space Administration (NASA), NASA's Jet Propulsion Laboratory (JPL), the California Institute of Technology (Caltech), and the Southwest Research Institute (SWRI).

NASA Jet Propulsion Laboratory (JPL): is NASA's lead center for robotic exploration of the solar system, managed by the California Institute of Technology (Caltech).

NASA Europa Clipper Team: refers to the large, international group of scientists and engineers at NASA, JPL (Jet Propulsion Laboratory), and the JHU Applied Physics Laboratory (APL) who are working together to build, launch, and operate the Europa Clipper spacecraft and its instruments.

ΔG (Gibbs free energy change): indicates whether a chemical reaction or physical process is spontaneous at constant temperature and pressure.

NASA's Europa Clipper mission: aims to investigate Jupiter's moon Europa to determine if it has the necessary conditions to support life.

References

- [1] Anderson, J. D., Lau, E. L., Sjogren, W. L., Schubert, G., and Moore, W. B. (1998). Europa's differentiated internal structure: Inferences from four Galileo encounters. *Science*, 281(5385), 2019-2022. <https://doi.org/10.1126/science.281.5385.2019>
- [2] Brown, M. E., and Hand, K. P. (2013). Salts and radiation products on the surface of Europa. *The Astronomical Journal*, 145(4), 110. <https://doi.org/10.1088/0004-6256/145/4/110>
- [3] Brown, M. E., and Hill, R. E. (1996). Discovery of an extended sodium atmosphere around Europa. *Nature*, 380, 229-231. <https://doi.org/10.1038/380229a0>
- [4] Carlson, R. W., Johnson, R. E., & Anderson, M. S. (1999). Sulfuric acid production on Europa: The radiolysis of sulfur in water ice. *Science*, 286(5437), 97-99. <https://doi.org/10.1126/science.286.5437.97>
- [5] Cassidy, T. A., Johnson, R. E., McGrath, M. A., Wong, M. C., & Cooper, J. F. (2007). The spatial morphology of Europa's near-surface O₂ atmosphere. *Icarus*, 191(2), 755-764. <https://doi.org/10.1016/j.icarus.2007.06.013>

- [6] Chyba, C. F., and Phillips, C. B. (2001). Possible ecosystems and the search for life on Europa. *Proceedings of the National Academy of Sciences*, 98(3), 801-804. <https://doi.org/10.1073/pnas.98.3.801>
- [7] Dalton, J. B., Prieto-Ballesteros, O., Kargel, J. S., et al. (2005). Spectral comparison of heavily hydrated salts with disrupted terrains on Europa. *Icarus*, 177(2), 472-490. <https://doi.org/10.1016/j.icarus.2005.03.026>
- [8] Greeley, R., Chyba, C. F., Head, J. W., McCord, T. B., McKinnon, W. B., Pappalardo, R. T., and Moore, J. M. (2000). Geology of Europa. In R. Greenberg and R. Pappalardo (Eds.), *Jupiter: The Planet, Satellites and Magnetosphere* (pp. 329-362). Cambridge University Press.
- [9] Grasset, O., Dougherty, M. K., Coustenis, A., et al. (2013). JUPITER ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterize the Jupiter system. *Planetary and Space Science*, 78, 1-21. <https://doi.org/10.1016/j.pss.2012.12.002>
- [10] Greenberg, R. (2005). *Europa: The Ocean Moon: Search for an Alien Biosphere*. Springer.
- [11] Greenberg, R., Geissler, P., Hoppa, G. V., et al. (2002). Tectonic processes on Europa: Tidal stresses, mechanical response, and visible features. *Reviews of Geophysics*, 40(1), 1004. <https://doi.org/10.1029/2000RG000092>
- [12] Hall, D. T., Strobel, D. F., Feldman, P. D., McGrath, M. A., and Weaver, H. A. (1995). Detection of an oxygen atmosphere on Jupiter's moon Europa. *Nature*, 373(6516), 677-679. <https://doi.org/10.1038/373677a0>
- [13] Hand, K. P., and Carlson, R. W. (2015). Europa's surface color suggests an ocean rich with sodium chloride. *Geophysical Research Letters*, 42(9), 3174-3178. <https://doi.org/10.1002/2015GL063559>
- [14] Hand, K. P., and Chyba, C. F. (2007). Empirical constraints on the salinity of the European ocean and implications for a thin ice shell. *Icarus*, 189(2), 424-438. <https://doi.org/10.1016/j.icarus.2006.12.028>
- [15] Hand, K. P., Chyba, C. F., Carlson, R. W., and Cooper, J. F. (2006). Clathrate hydrates of oxidants in the ice shell of Europa. *Astrobiology*, 6(3), 463-482. <https://doi.org/10.1089/ast.2006.0063>
- [16] Hussmann, H., Sohl, F., & Spohn, T. (2006). Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. *Icarus*, 185(1), 258-273. <https://doi.org/10.1016/j.icarus.2006.06.005>
- [17] Hussmann, H., Spohn, T., and Wiczerkowski, K. (2002). Thermal equilibrium states of Europa's ice shell: Implications for internal ocean thickness and surface heat flow. *Icarus*, 156(1), 143-151. <https://doi.org/10.1006/icar.2001.6776>
- [18] Jia, X., Kivelson, M. G., Khurana, K. K., and Kurth, W. S. (2018). Evidence of a plume on Europa from Galileo magnetic and plasma wave signatures. *Nature Astronomy*, 2(6), 459-464. <https://doi.org/10.1038/s41550-018-0450-z>
- [19] Johnson, R. E., Carlson, R. W., Cooper, J. F., Paranicas, C., Moore, M. H., and Wong, M. C. (2009). Europa's surface composition. In R. T. Pappalardo, W. B. McKinnon, & K. Khurana (Eds.), *Europa* (pp. 507-527). University of Arizona Press.
- [20] Kivelson, M. G., Khurana, K. K., Russell, C. T., et al. (1999). Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment. *Journal of Geophysical Research: Space Physics*, 104(A3), 4609-4625. <https://doi.org/10.1029/1998JA900095>
- [21] Kivelson, M. G., Khurana, K. K., and Volwerk, M. (2000). The permanent and inductive magnetic moments of Ganymede. *Icarus*, 157(2), 507-522. <https://doi.org/10.1006/icar.2002.6834>
- [22] Leblanc, F., Johnson, R. E., and Brown, M. E. (2002). Europa's sodium atmosphere: An ocean source? *Icarus*, 159(1), 132-144. <https://doi.org/10.1006/icar.2002.6893>
- [23] Libes, S. M. (2011). Introduction to marine biogeochemistry (2nd ed.). Academic Press.
- [24] McCord, T. B., Hansen, G. B., Matson, D. L., et al. (1998). Salts on Europa's surface detected by Galileo's Near Infrared Mapping Spectrometer. *Science*, 280(5367), 1242-1245. <https://doi.org/10.1126/science.280.5367.1242>
- [25] McCord, T. B., Orlando, T. M., Teeter, G., et al. (2001). Thermal and radiation stability of salts on Europa's surface. *Journal of Geophysical Research: Planets*, 106(E12), 33175-33184. <https://doi.org/10.1029/2000JE001407>
- [26] NASA. (2024a). Europa Clipper Overview. Retrieved from <https://www.nasa.gov/europa/clipper/>
- [27] NASA. (2024b). Europa Clipper Mission Timeline. Retrieved from <https://www.jpl.nasa.gov/missions/europa-clipper>
- [28] NASA Europa Clipper Team. (2020). Magnetic induction and ocean detection of Europa [Illustration]. In Induced magnetic field from Europa's subsurface ocean. [reddit.com+15science.nasa.gov+15europa.nasa.gov+15](https://www.reddit.com/r/15science.nasa.gov+15europa.nasa.gov+15)
- [29] NASA Jet Propulsion Laboratory (1998). Various landscapes and surface features on Europa [Illustration]. missions to Jupiter | Galileo mission. NASA/JPL/DLR.
- [30] NASA Jet Propulsion Laboratory. (2024). Exosphere and atmosphere of Europa [Artist's concept].
- [31] NASA/JPL-Caltech (2021). Europa Clipper at Europa [Illustration]. NASA / Jet Propulsion Laboratory. <https://science.nasa.gov/image-detail/europa-clipper-at-europa-illustration-6x9/>
- [32] NASA / JPL-Caltech (2024). Poised for science: NASA's Europa Clipper instruments are all aboard. NASA / Jet Propulsion Laboratory. <https://www.nasa.gov/centers-and-facilities/jpl/poised-for-science-nasas-europa-clipper-instruments-are-all-aboard>
- [33] NASA/JPL-Caltech/ SWRI. (2020). Europa spectral reflectance data. NASA Planetary Data System (PDS). <https://pds.nasa.gov>

- [34] NASA/JPL/University of Arizona (2019). Blocks in the European crust provide more evidence of subterranean ocean [Illustration]. NASA Europa Clipper. Retrieved from <https://europa.nasa.gov/resources/157/blocks-in-the-european-crust-provide-more-evidence-of-subterranean-ocean/>
- [35] Pappalardo, R. T., and Barr, A. C. (2004). The origin of domes on Europa: The role of thermally induced compositional diapirism. *Geophysical Research Letters*, 31(1), L01701. <https://doi.org/10.1029/2003GL018578>
- [36] Pappalardo, R. T., Head, J. W., Greeley, R., et al. (1999). Geologic evidence for solid-state convection in Europa's ice shell. *Nature*, 391, 365-368. <https://doi.org/10.1038/34862>
- [37] Peale, S. J., Cassen, P., and Reynolds, R. T. (1979). Melting of Io by tidal dissipation. *Science*, 203(4383), 892-894. <https://doi.org/10.1126/science.203.4383.892>
- [38] Phillips, C. B., and Pappalardo, R. T. (2014). Europa Clipper mission concept: Exploring Jupiter's Ocean moon. *Eos, Transactions American Geophysical Union*, 95(20), 165-167. <https://doi.org/10.1002/2014EO200002>
- [39] Plainaki, C., Milillo, A., Mura, A., et al. (2013). Exospheric O₂ densities at Europa: An assessment of the role of thermal desorption and sputtering. *Planetary and Space Science*, 82-83, 10-17. <https://doi.org/10.1016/j.pss.2013.03.004>
- [40] Plainaki, C., Massetti, S., Mura, A., et al. (2015). The role of sputtering and radiolysis in the generation of Europa's exosphere. *Icarus*, 245, 306-319. <https://doi.org/10.1016/j.icarus.2014.08.027>
- [41] Poston, M. J., Hand, K. P., and Carlson, R. W. (2017). Experimental constraints on the chemical composition of Europa's surface: Radiolysis of NaCl and implications for a chloride-rich ocean. *Journal of Geophysical Research: Planets*, 122(12), 2644-2658. <https://doi.org/10.1002/2017JE005387>
- [42] Prockter, L. M., Patterson, G. W., Schenk, P. M., et al. (2002). Morphology of European bands at high resolution: A mid-ocean ridge analog. *Geophysical Research Letters*, 29(24), 2144. <https://doi.org/10.1029/2002GL015984>
- [43] Reuters (2024). NASA prepares for Europa Clipper launch to explore icy moon. Retrieved from <https://www.reuters.com/>
- [44] Roth, L., Saur, J., Retherford, K. D., et al. (2014). Transient water vapor at Europa's south pole. *Science*, 343(6167), 171-174. <https://doi.org/10.1126/science.1247051>
- [45] Schilling, N., Neubauer, F. M., and Saur, J. (2007). Time-varying interaction of Europa with the Jovian magnetosphere: Constraints on the conductivity of Europa's subsurface ocean. *Icarus*, 192(1), 41-55. <https://doi.org/10.1016/j.icarus.2007.06.016>
- [46] Spencer, J. R., & Denk, T. (2010). Formation of Iapetus' extreme albedo dichotomy by exogenically triggered thermal ice migration. *Science*, 327(5964), 432-435. <https://doi.org/10.1126/science.1177132>
- [47] Spencer, J. R., Tamppari, L. K., Martin, T. Z., and Travis, L. D. (1999). Temperatures on Europa from Galileo photopolarimeter-radiometer: Nighttime thermal anomalies. *Science*, 284(5419), 1514-1516. <https://doi.org/10.1126/science.284.5419.1514>
- [48] Time. (2017). Could there be life on Europa? Retrieved from <https://time.com>
- [49] Trumbo, S. K., Brown, M. E., and Hand, K. P. (2019). Sodium chloride on the surface of Europa. *Science Advances*, 5(6), eaaw7123. <https://doi.org/10.1126/sciadv.aaw7123>
- [50] Vance, S. D., Bouffard, M., Choukroun, M., and Sotin, C. (2014). Ganymede's internal structure including thermodynamics of magnesium sulfate oceans in contact with ice. *Planetary and Space Science*, 96, 62-70. <https://doi.org/10.1016/j.pss.2014.03.011>
- [51] Vance, S. D., Hand, K. P., and Pappalardo, R. T. (2016). Geophysical controls of chemical disequilibria in Europa. *Geophysical Research Letters*, 43(10), 4871-4879. <https://doi.org/10.1002/2016GL068547>
- [52] Vance, S. D., Hand, K. P., and Pappalardo, R. T. (2018). Science goals and objectives for the Europa Clipper mission. *Space Science Reviews*, 214(5), 1-57. <https://doi.org/10.1007/s11214-018-0511-9>
- [53] Wired (2000). Deep-sea life in extreme environments. Retrieved from <https://www.wired.com/>
- [54] Zahnle, K., Schenk, P., Levison, H., and Dones, L. (2003). Cratering rates in the outer Solar System. *Icarus*, 163(2), 263-289. [https://doi.org/10.1016/S0019-1035\(03\)00048-4](https://doi.org/10.1016/S0019-1035(03)00048-4)
- [55] Zimmer, C., Khurana, K. K., and Kivelson, M. G. (2000). Subsurface oceans on Europa and Callisto: Constraints from Galileo magnetometer observations. *Icarus*, 147(2), 329-347. <https://doi.org/10.1006/icar.2000.6456>