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Conditions and Prospects for Extraterrestrial Life: A Literature-Based Review of Habitability Factors

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Abstract. The search for extraterrestrial life has become a central issue in astronomy and astrobiology, especially as recent national and international space exploration programs emphasize its importance. This study aims to review the theoretical foundations and current evidence for extraterrestrial habitability, focusing on the key conditions necessary for life. Using a literature analysis approach, the research synthesizes findings from planetary science, space probe data, and exoplanet discoveries to evaluate the roles of liquid solvents, energy sources, temperature ranges, atmospheric composition, and geological activity in supporting life. The results highlight that Europa and Enceladus, with subsurface oceans and tidal heating, present the strongest evidence for habitability, while Titan expands possibilities for non-aqueous life, and exoplanets such as Kepler-22b and Kepler-452b remain promising but poorly constrained candidates. However, the study is limited by reliance on secondary data and theoretical assumptions, lacking direct observational evidence of atmospheres or biosignatures. Future research should integrate advanced telescope observations, in-situ exploration missions, and interdisciplinary modeling to further assess the distribution and diversity of potential extraterrestrial life.

Keywords: extraterrestrial life, habitability, exoplanets, icy moons, astrobiology

1. Introduction

The existence of extraterrestrial life is one of the most profound and long-standing scientific issues in both astronomy and life sciences. Since antiquity, humanity has speculated on whether life exists beyond Earth, but only in recent decades have technological advancements provided the tools to begin answering this question systematically. With the rapid development of spacecraft detection technologies, deep-space probes, and high-precision space telescopes, researchers have gradually deepened their understanding of potentially habitable celestial bodies both inside and outside the solar system. These advances have not only expanded the catalog of known exoplanets but also revealed compelling evidence of subsurface oceans, volatile chemistry, and dynamic geological activity within icy moons of our solar system. In 2024, China issued the National Space Science Medium- and Long-Term Development Plan (2024–2059), which explicitly identifies the search for extraterrestrial life as a strategic research priority. The plan emphasizes that exploring extraterrestrial life is essential for addressing fundamental scientific questions such as the origin and evolution of the universe, the nature of time, space, and gravity, as well as the laws governing matter and life in

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the space environment [1]. This initiative also reflects broader international trends: NASA’s James Webb Space Telescope, ESA’s JUICE mission to Jupiter’s icy moons, and planned deep-space exploration projects by multiple countries all signal a global effort to probe habitability conditions beyond Earth. Together, these programs highlight not only the scientific significance of astrobiology but also its role in advancing technological innovation and enhancing international competitiveness in space exploration and astrophysics.

Previous research has identified several universal conditions necessary for life: the presence of liquid water or other solvents, a stable and long-term energy supply, a suitable temperature range, an atmospheric protective layer, and diverse organic chemical components [2]. These criteria form the basis for evaluating planetary habitability and serve as guiding principles for ongoing and future missions. For instance, icy moons such as Europa and Enceladus, with their subsurface oceans and tidal heating, are considered prime candidates for hosting microbial life, while Titan offers a unique model for exploring non-aqueous life chemistry. On the exoplanetary front, discoveries such as Kepler-22b and Kepler-452b have broadened the scope of potentially habitable worlds and pushed the frontier of comparative planetology.

This article will systematically review the key conditions for the existence of extraterrestrial life—liquid water or alternative solvents, stable energy sources, suitable temperature ranges, and atmospheric and chemical compositions—and apply these criteria to analyze the habitability potential of icy moons within the solar system and selected terrestrial exoplanets. In doing so, it aims to provide a comprehensive synthesis of current knowledge, highlight existing gaps, and offer directions for future exploration and interdisciplinary research.

2. Literature review

The earliest research on extraterrestrial life was when astronomers proposed the concept of "habitable zone". Kasting et al. first proposed the theory of stellar habitable zone, arguing that if a planet is within the habitable zone of a star, liquid water may exist on the planet's surface, and therefore it has the possibility of nurturing life [3]. With the improvement of observation technology, research has developed from theoretical models to specific astronomical detection. After the launch of NASA's Kepler Space Telescope in 2009, a large number of Earth-like planets were discovered, some of which are located in the habitable zone, such as Kepler-22b and Kepler-452b. These discoveries have promoted the study of the habitability of exoplanets. In the solar system, Jupiter's Europa and Saturn's Enceladus have become the focus. The Cassini-Huygens probe's observations of Enceladus showed active ice plumes on its surface and detected water vapor, hydrogen molecules and organic matter [4], indicating that the underground ocean may have energy and chemical conditions similar to those of the Earth's deep-sea hydrothermal vents. Under the thick ice on Europa's surface, it is believed that there is a global liquid ocean, and Jupiter's strong tidal heating provides a continuous energy source [5]. Titan, due to the presence of many methane lakes and complex chemical processes, is considered an ideal place to explore the possibility of "non-water-based life" [6]. Previous studies have gradually formed a general framework for the existence of extraterrestrial life, including liquid solvents, energy supply, stable temperature, and diverse organic chemistry. However, these studies also have shortcomings. There is a lack of direct observation of the atmospheric composition and internal structure of exoplanets. The detection of icy satellites is still limited by technical conditions. In the future, with the continuous development of the James Webb Space Telescope and China's planned deep space exploration missions, people may obtain more accurate data and further confirm or revise existing theories.

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3. Conditions for extraterrestrial life

3.1. Liquid water or alternative solvents

Liquid water is widely considered one of the most important prerequisites for life to exist. This is due to its unique physical and chemical properties. As a polar molecule, it can dissolve a wide variety of organic and inorganic substances, providing an excellent medium for complex chemical reactions. Secondly, the high specific heat capacity of water buffers against drastic temperature fluctuations, thereby maintaining a relatively stable environment conducive to life. Hydrogen bonds exist between water molecules, allowing it to remain liquid even when temperature or pressure fluctuates. This stable state is conducive to the continued development of life. On Earth, whether in oceans, lakes, or groundwater systems, nearly all life depends on liquid water for survival, making liquid water a primary consideration in the search for extraterrestrial life.

Not all locations in the universe offer conditions for the long-term, stable existence of water. On some celestial bodies, the surface temperature is so low that water freezes; on others, the temperature is so high that water evaporates quickly. Therefore, scientists have proposed the concept of "alternative solvents," which suggests that under certain conditions, other liquids can act similarly to water. For example, the extremely cold methane and ethane liquid lakes on the surface of Titan, although the temperature is very low, these hydrocarbons also have a certain solubility and can serve as a reaction medium, which provides the possibility of "non-water-based life" [7]. Liquid water is the ideal solvent for extraterrestrial life, but in extreme environments, alternative solvents such as methane, ethane, and ammonia may also be the site of life chemical reactions. Therefore, when searching for extraterrestrial life, people cannot just focus on "water-based life" but must expand the scope to "liquid solvent life". This will greatly broaden human cognition of the boundaries of life.

3.2. Stable energy source

The existence and development of life require a continuous supply of energy. Energy not only drives metabolic reactions, but also maintains the stability of the structure of organisms and the transmission of information. The main source of energy on Earth is sunlight, and photosynthesis enables the biosphere to thrive. However, in extraterrestrial environments, sunlight is not always available, especially on planets without stellar radiation or covered by thick ice. Therefore, other forms of energy are particularly important.

Stellar radiation remains the most common form of energy. Exoplanets in the habitable zone receive just the right amount of sunlight—the energy intensity is neither high enough to evaporate liquid solvents nor low enough to freeze them. This stable radiation environment is believed to be crucial for the formation and survival of life [8]. The energy inside the planet also plays a vital role. The decay of radioactive elements, the heat released when the planet cools, and the tidal interaction with the parent planet all provide a continuous supply of energy for extraterrestrial life. Jupiter's tidal force causes the interior of Europa to continue to heat up due to friction, thereby maintaining its underground ocean in a liquid state. Similarly, geological movements and geysers on Enceladus also indicate the existence of a powerful internal energy mechanism.

Chemical energy provides another pathway for life. The emergence of deep-sea hydrothermal vent ecosystems on Earth shows that life does not need to rely on sunlight to survive, but can obtain energy through chemical reactions of inorganic substances such as sulfides and hydrogen. This discovery provides a strong analogy for the existence of life on icy planets and lightless exoplanets. A stable energy supply is the second most important condition for the existence of extraterrestrial

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life. Whether the energy comes from stellar radiation, internal heat of a planet, or chemical reaction processes, as long as it can be provided continuously for a long time, it may provide the necessary power for life activities. If future exploration missions can find these energy mechanisms, it will greatly enhance our understanding of the potential distribution of extraterrestrial life.

3.3. Suitable temperature range

Temperature is one of the key environmental factors that determines whether life can exist. Chemical reactions in organisms are typically very sensitive to temperature. Excessively high temperatures can cause the decomposition of organic molecules and proteins, while excessively low temperatures can sharply reduce metabolic reaction rates or even completely halt them. Most life on Earth exists between tens of degrees Celsius and tens of degrees Celsius below zero. This temperature range creates an ideal environment for the existence of liquid water and biochemical reactions. Therefore, in the search for extraterrestrial life, suitable temperatures, like liquid solvents, are considered a core requirement.

In a stellar system, temperature is primarily determined by the distance of a planet from its star—in other words, whether it is located in the so-called "habitable zone." Planets in this zone can have liquid water on their surfaces, neither too close for all the water to evaporate nor too far for the water to freeze permanently. For example, Kepler-22b and Kepler-452b are considered habitable planets because they are in the habitable zone. However, a planet's surface temperature isn't solely determined by its distance from the star; the presence of an atmosphere is also crucial. A thick atmosphere acts as a greenhouse effect, stabilizing and maintaining the planet's surface temperature. Celestial bodies without an atmosphere can experience large temperature swings between day and night or experience extreme climates. Geology and internal energy also influence temperature. For example, Europa and Enceladus have extremely low surface temperatures, but tidal heating and internal heat allow their subsurface oceans to remain liquid for extended periods, creating a relatively stable "potential breeding ground for life." This suggests that on some icy worlds, the ideal temperature may lie not on the surface but within the subsurface environment. This ideal temperature range depends on both stellar illumination and atmospheric regulation and internal energy. Only in such an environment can liquid solvents exist stably and chemical reactions related to life proceed smoothly. Therefore, temperature conditions are a key indicator of the habitability of a planet or satellite.

3.4. Atmosphere and chemical composition

The atmosphere plays an indispensable role in the formation and maintenance of life. It acts as a natural barrier to protect against direct exposure to high-energy particles, ultraviolet rays, and cosmic rays, thereby preventing damage to the molecular structure of potential life forms. Moreover, the atmosphere can regulate the surface temperature of celestial bodies through the greenhouse effect, maintain a relatively stable climate, and thus provide conditions for the existence of liquid solvents. For example, the Earth is suitable for life, largely due to the temperature regulation effect of carbon dioxide and water vapor in the atmosphere [9]. The atmosphere itself is also an important source of material for life activities. It provides the gases needed for breathing and performs material exchange and energy distribution tasks through climate cycles [9]. For extraterrestrial life, the carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur elements contained in the atmosphere are very important. These are the fundamental substances for creating organic molecules and supporting complex metabolic processes. The presence of methane, ammonia, and other nitrogen-

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containing compounds makes possible a variety of chemical reactions. The atmosphere is closely linked to geological activities. Volcanic eruptions, crustal movements, and other processes continuously replenish gases to the atmosphere, thereby maintaining the dynamic balance of the atmosphere. Titan's thick atmosphere contains large amounts of nitrogen and methane, and its complex organic chemical processes make it a promising research area for the search for non-aqueous life. In contrast, although Mars lies on the edge of the habitable zone, its thin atmosphere lacks sufficient protection, making it difficult for the Martian surface to sustain liquid water and a stable climate over a long period of time.

This shows that the atmosphere is both a protective barrier and a breeding ground for life. The thickness, composition, and relationship with geological activity of the atmosphere collectively determine whether a celestial body is a suitable environment for life. Without a stable and chemically diverse atmosphere, even if other conditions are met, life cannot persist and develop over the long term.

4. Analysis of potentially habitable objects

Based on existing observations and exploration results, the scientific community generally agrees that some icy moons and some terrestrial exoplanets in the solar system are potentially habitable. Jupiter's Europa has attracted considerable attention due to the presence of a global liquid ocean beneath its thick ice layer. Tidal heating provides sufficient energy within its interior to sustain water-rock interactions and chemical circulation, remarkably similar to the conditions found in deep-sea hydrothermal vents on Earth. Therefore, Europa is considered one of the most likely candidates for the development of life in the solar system.

Enceladus also has a strong potential for habitability. The Cassini probe observed spectacular water vapor plumes in Enceladus's south polar region, emitting water, molecular hydrogen, and complex organic matter. This suggests that Enceladus's internal ocean contains an energy source and the conditions for synthetic reactions. These findings indicate active geological processes on Enceladus and provide direct evidence for the possibility of biochemical activity. Titan, with its thick atmosphere and surface lakes of methane and ethane, is a unique example of non-aqueous life. Despite its extremely low surface temperatures, complex hydrocarbon reactions could potentially foster chemical systems distinct from those found on Earth, broadening our understanding of life's diversity and extreme adaptability. Regarding exoplanets, Kepler-22b and Kepler-452b are considered potential hosts for life due to their location within their star's habitable zone. They are roughly the same size as Earth and could theoretically harbor liquid water within the right temperature range. While direct observations of their atmospheric composition and geological activity are lacking, the underlying conditions appear somewhat habitable. Europa and Enceladus are considered the most promising candidates for the discovery of extraterrestrial life due to their direct evidence and well-defined environmental conditions. Titan and other Earth-like exoplanets offer new avenues for exploring the boundaries and types of life.

5. Conclusion

Drawing on literature analysis, this study summarizes the key conditions for the existence of extraterrestrial life: liquid water or alternative solvents, a stable energy supply, a suitable temperature range, an atmosphere and its essential components, and sustained geological and chemical activity. These factors interact to determine whether a celestial body is a potential habitat for life. Specifically, Europa and Enceladus are considered the most promising candidates for

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finding life in the solar system due to their subsurface oceans, tidal heating, and active geyser activity. Titan offers new insights into the search for non-aqueous life. While direct observation data is lacking for exoplanets like Kepler-22b and Kepler-452b, their location in the habitable zone makes them prime targets for future observation.

Looking forward, with the advancement of deep space exploration and space telescope technology, humanity will achieve even greater breakthroughs in the search for extraterrestrial life. Spectral measurements of exoplanet atmospheres may reveal the presence of biosignature gases; in-depth exploration of icy moons may reveal the true nature of subsurface oceans; and the application of artificial intelligence and big data analysis can help improve research efficiency and accuracy. However, existing research is still limited by observation methods and theoretical assumptions, so the conclusions are uncertain. In future exploration, researchers must continue to promote scientific and technological innovation, interdisciplinary integration, and international joint exploration.

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