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Endogenous Radiolytic Production of Oxygen and Its Potential to Support Habitable Environments in Ocean Worlds

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Jan 2025

Contents

List of Figures

List of Tables

Acknowledgments

I would like to express my heartfelt gratitude to my supervisor, Dr. Truong Tuan Ngoc, for his incredible support and guidance throughout this project. His patience and expertise have taught me a lot and help shape my approach to research problems and critical thinking. His detailed feedbacks and encouragement has been helping me improve every single details of my work, connect my result to a bigger picture, and explore ideas that I wasn't sure about at first. For all of this, I am truly grateful. Dr. Ngoc's guidance has had a lasting impact on my development as a student who used to didn't really know much about how to conduct a research step by step.

I would also like to extend my sincere thanks to Dr. Tong Si Son, my teacher at USTH, for his valuable advices and lessons that went beyond technical knowledge. He has guided me in thinking more broadly and approaching challenges with maturity and open-mindedness.

Finally, I extend my thanks to USTH and Space and Applications Department for providing the resources and environment helping me conducting this project.

1 Introduction

Oxygen plays a vital role in both Earth's biological systems and the search for extraterrestrial life due to its unique biological, chemical, and environmental properties. Oxygen acts as the terminal electron acceptor in aerobic respiration, providing ten times more energy than anaerobic processes, which supports complex metabolic activities and enables the growth of larger and more diverse life forms [1][2]. On Earth, its appearance in the atmosphere marked key evolutionary milestones, such as the Great Oxidation Event, paving the way for complex life [1].

Beyond Earth, oxygen has been considered a potential biosignature, as its high abundance can indicate life, though its reliability depends on the specific context of the planetary environment [2]. With its stable chemical properties, high energy yield, and compatibility with water-rich environments, oxygen is indispensable not only for supporting complex life but also for detecting life on other planets.

This is particularly relevant for Ocean Worlds in our Solar system, which harbor global subsurface oceans beneath their icy shells (see Figure 1) [3]. Europa, one of Jupiter's largest moons, is of particular interest. Beneath its icy crust, Europa harbor a global subsurface liquid water ocean, estimated to be about 100 km thick [4] and contain more than twice the water volume of all Earth's oceans combined [5]. Due to its promising potential to find some form of life in its subsurface liquid water ocean, Europa is a compelling focus for astrobiological research, particularly regarding habitability. Ongoing missions, such as NASA's Europa Clipper, which will arrive at Europa in the next five years, and ESA's Jupiter Icy Moons Explorer (JUICE) are aimed to explore Europa's surface and subsurface environments to better understand its potential to support life [6] [7].

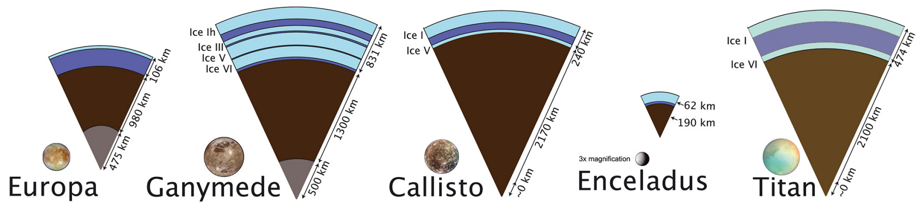

Figure 1: Schematics showing likely internal structures for known Ocean Worlds.

We aim to investigate the process of production of oxygen through water radiolysis and radioactive decay (see Figure 2) [8], focus on the γ radiation during the decay of potassium, which occurs in only 10% of its decay events. This focus is due to γ radiation providing a well-characterized and quantifiable energy source for radiolysis, supported by available data and models. Other decay pathways, such as α and β emissions were excluded to simplify the analysis and emphasize the role of γ radiation as a significant contributor to radiolytic processes. This choice enables a clear and focused discussion, while leaving room for future work to incorporate the contributions of other radiative processes. The key aspect is to answer these following key questions:

- How much oxygen can be produced through γ emission of ^{40}K decay in Europa's ocean?
- How do different environment factors affect radiolytic oxygen production?
- What are the implications for Europa's potential habitability?

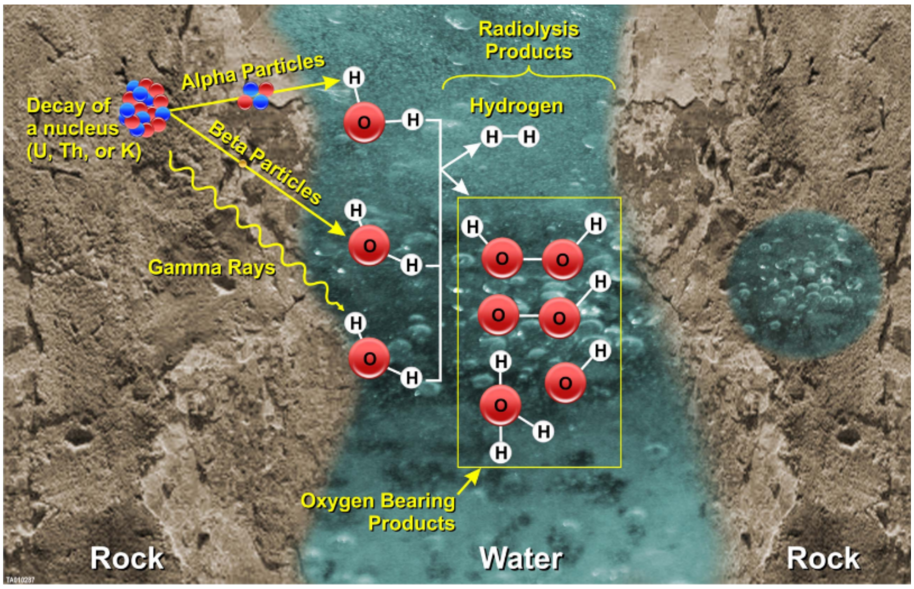

Figure 2: Summary of the process of water radiolysis by radionuclides. The radiolysis products are the result of several physico-chemical steps that follow the excitation/ionization of water by radiation.

The results may help understanding the habitability of Ocean Worlds [9], particularly the processes that could support life in Europa's ocean [10]. Furthermore, recent astronomical observations have revealed numerous water-rich exoplanets, ranging from super-Earths size to Neptune-sized worlds [11], highlighting the broader relevance of understanding the chemical evolution in distant water worlds.

2 Theoretical Background

2.1 Role of water radiolysis and potassium decay in oxygen production

Radiolysis, the process of breaking down water molecules through ionizing radiation, plays a significant role in oxygen production in oceanic environments. This mechanism is driven by the decay of naturally occurring radioactive isotopes such as potassium (^{40}K), uranium-235 (^{235}U), uranium-238 (^{238}U), and thorium (^{232}Th). These radioactive elements emit α-particles, β-particles, and γ-rays during their decay, which interact with water molecules to produce reactive species and molecular oxygen [12] [13]. The radiolysis process is described by:

$$\mathrm{H_2O} \xrightarrow{\text{radiation}} e^-_{\mathrm{aq}}, \cdot\mathrm{H}, \cdot\mathrm{OH}, \mathrm{H^+}, \mathrm{OH^-}, \mathrm{O_2}, \mathrm{O_2^-}, \mathrm{H_2}, \mathrm{H_2O_2}, \mathrm{HO_2^-}, \mathrm{HO_2}$$

Molecular oxygen is not formed as a primary product of water radiolysis, but appears via secondary reactions. When ionizing radiation interacts with water, it produces short lived reactive species such as the hydrated electron (e^-_{aq}), hydrogen atoms (H), hydroxyl radicals (OH), H^+ and OH^- ions, and hydroperoxyl radicals (HO_2). These species undergo secondary reactions to form molecular products, including hydrogen gas (H_2), hydrogen peroxide (H_2O_2), and molecular oxygen (O_2) [14]. A kinetic model of water radiolysis describing the radiation chemical transformations of aqueous solutions has been developed by Ershov and Gordeev in 2007 [15]. Some of the key reactions leading to oxygen formation can be found in Table 1.

Table 1: Some key reactions leading oxygen formation and their rate constants and activation energies.

No.	Reaction	k ($M^{-1}s^{-1}$) [16]	E_a (kJ mol^{-1}) [15]
1	$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	8.1×10^5	24.7
2	$HO_2 + H_2O_2 \rightarrow O_2 + OH + H_2O$	3.7	20.0
3	$OH + HO_2 \rightarrow O_2 + H_2O$	7.1×10^9	12.6
4	$OH + O_2^- \rightarrow O_2 + OH^-$	9.96×10^9	12.6
5	$HO_2 + O_2^- \rightarrow O_2 + HO_2^-$	9.5×10^7	8.8
6	$O_2^- + O_2^- \rightarrow O_2 + HO_2^- + OH^-$	0.3	12.6
7	$O_2^- + H_2O_2 \rightarrow O_2 + OH^- + OH$	16	20
8	$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2$	–	–

Potassium-40 (^{40}K) is a key contributor to radiolytic oxygen production due to its abundance and decay pathways. Approximately 89% of ^{40}K decays via β-emission, while the remaining 11% undergo electron capture, producing γ-radiation. The process can be expressed by:

$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + \beta$$

$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ar} + \gamma$$

In Europa's subsurface ocean, radiolysis driven by ^{40}K could play a crucial role in generating oxidants like molecular oxygen. The presence of oxygen could support potential microbial ecosystems by providing a source of chemical energy for aerobic respiration [2].

2.2 Thresholds for microbial survival

Microbes are some of the most resilient forms of life on Earth, have adapted to survive in environments with limited resources, including low oxygen levels and minimal energy availability or even anoxic conditions. Their broad tolerance reflects their ability to switch to anaerobic metabolic pathways or enter a dormant state when oxygen levels are insufficient [17]. Additionally, extremophiles - organisms capable of thriving in extreme environmental conditions - demonstrate that life can adapt to remarkably low oxygen concentrations. In Jennifer Chu's study in 2016, certain microbes in Earth's oxygen minimum zones (OMZs) have been observed to survive at oxygen levels far below the sublethal thresholds of marine taxa. These extremophiles often rely on specialized metabolic strategies, such as anaerobic respiration or fermentation, and can enter highly efficient states of dormancy to conserve energy in resource-depleted environments [18].

These adaptations provide valuable analogs for life that might exist in energy-constrained and oxygen-depleted environments beyond Earth. For further details, refer to Section 3.5.

2.3 Geochemical element redistribution model for Europa

A model calculating how elements are extracted from Europa's silicate mantle and redistributed among its ocean, crust, and atmosphere using mass balance equations was developed by Zolotov and Shock in 2001 [19]. It is assumed that Europa's silicate mantle have a composition similar to CV-type carbonaceous chondrite meteorites, based on analogs used in planetary science for rocky bodies [20] [21]. These meteorites are rich in refractory elements like magnesium and potassium, and their chemical makeup provides a plausible baseline for Europa's Bulk Silicate Earth (BSE) [22]. The assumption is structured based a hierarchical framework that mirrors the geochemical reservoirs observed on Earth (see Figure 3) [19].

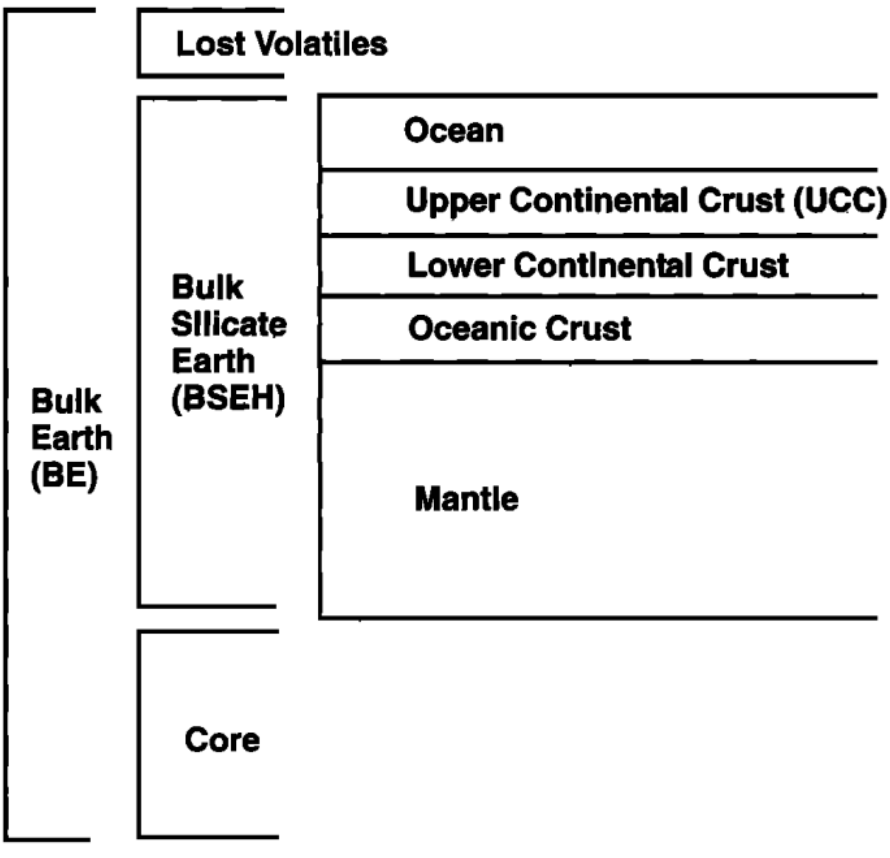

Figure 3: Relations between major terrestrial geochemical reservoirs (Zolotov and Shock, 2001).

The Bulk Earth (BE) encompasses all material on Europa, including the silicate mantle, crust, core, and lost volatiles, representing the total inventory of elements involved in geochemical processes. Within this framework, the core is a separate, dense reservoir primarily composed of metallic elements and is largely inaccessible for interaction with the ocean or crust. The Bulk Silicate Earth (BSEH) includes the mantle and crustal layers, excluding the core, and serves as primary reservoir for elements interacting with the ocean. The crust is further divided into the upper continental crust (UCC), lower continental crust, and oceanic crust. The ocean represents the most accessible reservoir for dissolved elements, particularly soluble species like potassium and sodium, and interacts extensively with the crust. The lost volatiles reservoir represents the elements or compounds that escape Europa's system through impact-driven ejection or atmospheric sputtering, representing a permanent loss from the cycle. The mantle, the largest silicate reservoir, is assumed to have a composition similar to carbonaceous chondrite meteorites, which serves as a baseline for modeling element extraction. Additionally, leaching, degassing and certain thermodynamics processes are assumed to be similar to Earth, this provides an opportunity to evaluate limits for elemental composition of the ocean based on the mass and assumed chondritic composition of silicate part of Europa, and a proposed thickness of the ocean, while keeping in mind terrestrial data on partitioning of elements among the mantle, ocean, and crustal geochemical reservoirs [22]. Specifically for potassium, the extraction factors can be mathematically expressed in Section 3.2.

3 Data and Methods

3.1 Energy of gamma radiation of potassium decay

The energy of the γ photon emitted during the electron capture decay of ^{40}K into ^{40}Ar is derived from the excess mass difference between the parent and daughter isotopes. This can be calculated using Einstein's mass-energy equivalence formula:

$$E_\gamma = (m_{40K} - m_{40Ar}) \cdot c^2$$

in which m_{40K} is 39.964008 amu, m_{40Ar} is 39.962384 amu and 1 amu = 931.478 MeV. Given that, the calculated energy is approximately 1.5 MeV. This value represents the γ radiation emitted during the decay of ^{40}K and will serve as a foundational parameter for all subsequent analyses conducted in this project. It represents a key input for quantifying radiolysis-driven chemical processes and evaluating the potential for oxygen production in Europa's subsurface ocean.

3.2 Potassium extraction and distributions on Europa

Potassium's decay via electron capture releases γ radiation, providing an energy source that influences radiolysis products in the ocean. Its redistribution among Europa's different reservoirs can be quantified using extraction factors ($\epsilon_0, \epsilon_1, \epsilon_2, \epsilon_{1a}$). For the purpose of this project, Europa's Bulk Silicate Earth (BSE) is assumed to have a composition analogous to carbonaceous chondrite meteorites, which are commonly used as a proxy in planetary science to model rocky bodies like Europa.

ϵ_0, the total extraction factor, quantifies the fraction of potassium redistributed from Europa's Bulk Silicate Earth (BSE) into all reservoirs, including the ocean, upper crust, and potential losses due to impact processes. ϵ_1, the partial extraction factor, focuses on the redistribution of potassium into the ocean and upper crust, excluding contributions to the core or losses to space. ϵ_2 is the factor that isolates the fraction of potassium transferred directly to the ocean.

These extraction factors can be expressed mathematically below, in which $M_K(BE)$ is the total mass of potassium in Europa's Bulk Earth (mantle plus core), $M_K(BSEH - UCC - O)$ is the mass of potassium remaining in the Bulk Silicate Earth (BSEH), including the lower mantle, lower crust, and oceanic crust, $M_K(UCC + O)$ is mass of potassium in the upper continental crust (UCC) and ocean, $M_K(BSEH)$ is mass of potassium in the Bulk Silicate Earth and $M_K(O)$ is mass of potassium in Europa's ocean. These values originate from theoretical modeling based on chondritic analogs by Zolotov and Shock in 2001 [19].

$$\epsilon_0 = \frac{M_K(BE) - M_K(BSEH - UCC - O)}{M_K(BE)}$$

$$\epsilon_1 = \frac{M_K(UCC + O)}{M_K(BSEH)}$$

$$\epsilon_2 = \frac{M_K(O)}{M_K(BSEH)}$$

Additionally, ϵ_{1a} is a refined model derived from ϵ_1 but adjusted based on the observed Na/ K ratios in Europa's atmosphere by M. Brown in 2001, which is ~ 25 [23]. This adjustment assumes that the Na/ K ratio in the ocean is accurately reflected in the atmosphere, with potassium and sodium being primary components of Europa's geochemical system.

Table 2: Concentration of Na and K under different extraction factors (Zolotov and Shock, 2001).

Extraction Factor	$\mathbf{C}_{Na}$ g/kg water	$\mathbf{C}_K$ g/kg water	$\mathbf{C}_K$ mol/kg water
ϵ_0 (all reservoirs)	9.3	2.5	0.064
ϵ_1 (ocean + upper crust)	1.1	1.6	0.041
ϵ_2 (ocean)	0.055	0.0027	0.000069
ϵ_{1a} (refined ϵ_1)	1.129	0.0768	0.00169

In this project, the concentration of ^{40}K was derived based on the assumption that the isotopic ratio of ^{40}K to total potassium is constant and similar to the known natural abundance on Earth, as there is currently no specific model for radioactive potassium (^{40}K) distribution in Europa's environment. This assumption allows for a preliminary estimation of radiolysis-driven oxygen production, acknowledging that ^{40}K constitutes only a small fraction (~ 0.0119% [24]) of the total potassium. While this approach provides a starting point, it introduces uncertainties, and future studies may refine these estimates as better data or models become available.

3.3 Evaluation of primary radiolysis products concentration

The concentration of radiolysis products through potassium decay γ emission can be calculated by:

$$C_{Pr} = 10^{-2} \cdot C_K \cdot A_K^{-1} \cdot E_\gamma \cdot G_{Pr} \cdot M^{-1} \cdot (1 - e^{-\lambda \cdot t})$$

in which C_{Pr} is concentration of the products (mol/L of water), C_K is amount of ^{40}K in the ocean, derived from the total potassium mass in the ocean determined by the extraction factors ϵ (g), A_K is the atomic weight of ^{40}K, E_γ is energy released upon the γ emission during decay (eV/ decay), G_{Pr} is the radiation chemical yields of the considered products ($\mu mol J^{-1}$), M is total water in the ocean (kg) [25].

The efficiency of these processes in water and aqueous solutions are quantified using the radiation chemical yield (G - value), expressed in the number of molecules formed or decomposed per unit of absorbed energy. This metric provides a standard measure of how effectively ionizing radiation drives chemical transformations. The table below summarizes the G - values for primary products of water radiolysis induced by γ radiation. While this study focuses on γ radiation, it is important to note that other types of ionizing radiation, such as α and β particles, also contribute to water radiolysis but are not included in this dataset.

Table 3: Radiation chemical yields (molecule/100 eV) used in calculation.

pH	$\mathbf{H^+}$ [26]	$\mathbf{OH^-}$ [26]	$\mathbf{e^-_{aq}}$ [26]	**H** [26]	$\mathbf{H_2}$ [26]	**OH**[26]	$\mathbf{H_2O_2}$ [26]	$\mathbf{O_2}$ [27]
0–2	3.45	0.4	3.05	0.6	0.45	2.95	0.8	0.225
4–9	3.4	0.7	2.7	0.6	0.45	2.8	0.7	0.225
12–13	3.6	0.55	3.05	0.55	0.4	2.9	0.75	0.2

3.4 Mass and pH of Europa's ocean

The thickness of Europa's outer water shell, encompassing both ice and liquid water, has been estimated by Zolotov and Shock in 2001, utilized a model based on Galileo spacecraft data to predict the thickness of Europa's ocean at three scenarios: 80 km, 100 km, and 150 km [19]. These values were derived by assuming a silicate mantle composition analogous to carbonaceous chondrites and incorporating the effects of radioactive heating, tidal forces, and differentiation processes during Europa's formation.

Table 4: Water Shell Thickness/ Mass on Europa.

Water Shell Thickness	80km	100km	150km
Mass	2.5×10^{21} kg	3×10^{21} kg	4.4×10^{21} kg

The exact pH of Europa's ocean remains unknown and is an open question, but current prediction suggests that it is most likely acidic (~ 4–6 [28] [29]), based on theoretical models, spacecraft measurements and assumptions that Europa's ocean composition may be shaped by leaching processes from a silicate mantle, similar to Earth's oceans but with different elemental ratios, however this value is not well constrained and does not account for all possible molecules and ions [29]. When water reacts with silicate rocks, it can release ions such as bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and magnesium (Mg_2^+), which influence the acidity or alkalinity of the water. Environments on Earth with similar pH ranges are alkaline lakes (e.g., Mono Lake) and hydrothermal systems (e.g., Lost City Hydrothermal Field). These environments host diverse microbial communities, providing analogs for potential ecosystems on Europa [30].

3.5 Threshold for microbial survival

Sublethal oxygen thresholds for various taxa extracted from experimental assessments are summarized in Table 5. These threshold represent the oxygen levels below which organisms begin to experience stress, such as slower growth or reduced activity, but do not immediately die. Algae are primary producers that generate oxygen in Earth's oceans. Hydrozoa and Scyphozoa are low-mobility aquatic organisms, such as jellyfish, that tolerate low oxygen. Polychaeta (worms) and Mollusca (clams, snails) are more mobile taxa. Crustacea taxa include organisms like shrimp, crabs, and active organisms that require higher oxygen levels. Chordata are complex animals with the highest oxygen requirements, such as fish [17].

While these thresholds provide insight into oxygen requirements for near-surface marine organisms, it is noted that certain extremophiles (such as bacteria, archaea, etc.) can even survive at much lower oxygen concentrations. Some bacteria found in Earth's oxygen minimum zones (OMZs) can tolerate oxygen levels as low as 1 to 10 nanomolar per liter. These extremophiles rely on specialized metabolic pathways, such as anaerobic respiration, or exist in dormant states to withstand harsh, low-oxygen environments [18].

Table 5: Median sublethal oxygen concentrations of benthic marine organisms and extremophiles.

Taxa	**Sublethal oxygen threshold (mg/L)**		**Ref.**
	Min.	**Max.**	
Algae	2.96	2.96	[31]
Hydrozoa	0.19	1.73	[32]
Scyphozoa	0.4	0.57	[32]
Anemones	0.71	1.43	[33] [34]
Polychaeta	0.57	3.43	[35] [36] [37] [38] [39]
Mollusca	0.57	3.24	[40] [41]
Crustacea	0.29	5	[42] [43]
Echinodermata	0.79	6.63	[44][45][46][47][48][49]
Chordata	1.94	9	[50][51][52][53][54][55]
Extremophiles	0.000032	0.00032	[18]

3.6 NASA's Juno observation on Europa's surface ice

The data about hydrogen and oxygen production rates on Europa's surface ice, derived from NASA's Juno's analysis of radiation-induced radiolysis, can be found in the table below. It was assumed that a portion of the H_2 and O_2 produced on the surface is transported to the subsurface ocean through fractures in the ice [56].

Parameter	**Value** [56]
Europa's surface ice	
H_2 production	1.5 ± 0.8 kg s^{-1}
O_2 production	12 ± 6 kg s^{-1}

Table 6: Hydrogen and oxygen production rates for Europa's surface ice.

4 Results and Discussion

4.1 Concentration of potassium on Europa's ocean

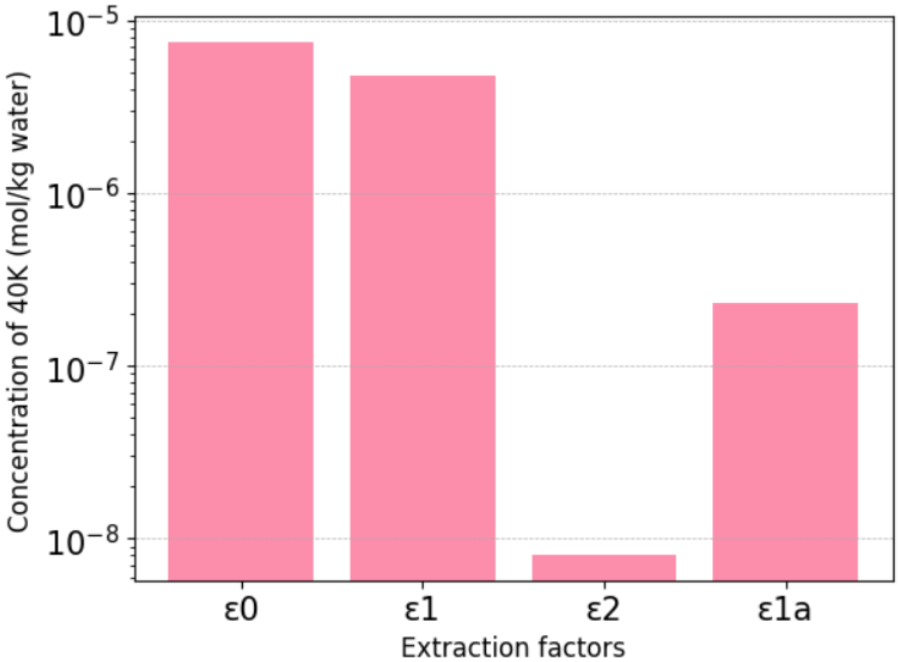

Figure 4: Molality concentration of ^{40}K in different reservoirs.

Under total extraction (ϵ_0), ^{40}K is distributed across all reservoirs, including the core, crust, and ocean. In the partial extraction model (ϵ_1), potassium is redistributed into the ocean and upper crust, excluding contributions from the core and potential losses. The ocean-specific extraction factor (ϵ_2) isolates potassium transferred directly to the ocean. The ϵ_{1a} model is adjusted based on the observed Na/K ratio in Europa's atmosphere.

ϵ_2 isolates the fraction of ^{40}K extracted directly into the ocean, excluding contributions from other reservoirs such as the crust or mantle. As observed, the very low level in ϵ_2 emphasizes the inefficiency of direct potassium transport, suggesting that most ^{40}K remains trapped in the crust or mantle. However, the adjusted ϵ_{1a} indicate that atmospheric Na/K ratios may provide a better proxy for estimating potassium contributions to the ocean.

4.2 Concentration of primary radiolysis products in different reservoirs

These models assume steady-state conditions and do not account for dynamic processes such as ocean circulation, hydrothermal activity, or temporal variations in radiation flux. Across all models, the most abundant product is hydrogen peroxide (H_2O_2), followed by hydroxyl radicals (OH), hydrated electrons (e^-_{aq}), protons (H^+), hydrogen (H_2), oxygen (O_2), and hydroperoxyl radicals (HO_2).

The ϵ_2 extraction factor, which isolates the ocean's share of ^{40}K, shows significantly lower concentrations of all radiolysis products compared to other models, indicating reduced oxidant production due to limited ^{40}K availability in the ocean. The dominated species play an important role in shaping the chemical environment. Hydrogen and oxygen are less abundant but still significant due to their role as sources for potential life, because even these reduced levels may support microbial ecosystems that rely on anaerobic or low-oxygen conditions.

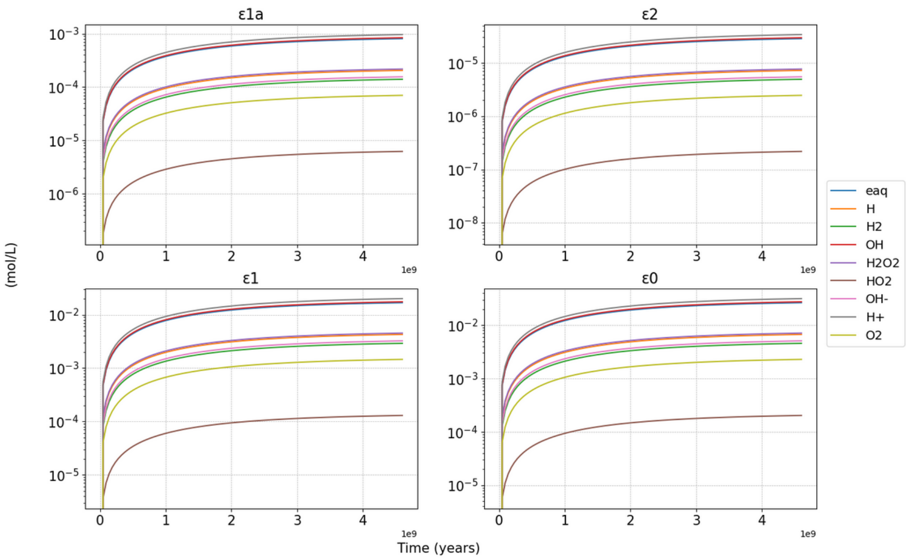

Figure 5: Concentration of some radiolysis products from ^{40}K γ emission under different extraction factors. $\epsilon 1a$ - refined ocean model, ϵ_1 - partial extraction of K into the upper continental crust and the ocean, ϵ_2 - fraction of K extracted into the ocean from Bulk Silicate Earth, ϵ_0 - total extraction of K into the core, the upper continental crust and the ocean.

4.3 Concentration of oxygen and comparison to sublethal oxygen levels of marine organisms and extremophiles

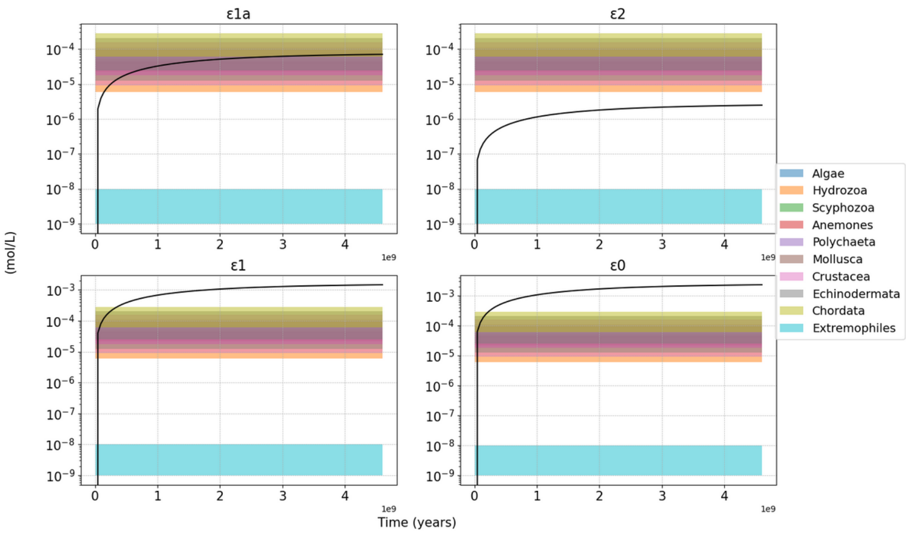

Figure 6: Comparison of O_2 produced with sublethal oxygen concentrations of benthic marine organisms and extremophiles.

For ϵ_0 and ϵ_1 models, O_2 concentrations exceed the sublethal thresholds of all marine taxa, indicating that oxygen levels would be sufficient to support even the most oxygen demanding near-surface marine organisms (Chordata) over time. However, when focusing on the ocean-only model ϵ_2, it can be seen that O_2 level are only sufficient to support extremophiles but not near-surface aquatic organisms with higher oxygen requirements. The refined model ϵ_{1a} shows intermediate oxygen levels, and can support near-surface organism that require less oxygen than Chordata.

When considering extremophiles, organisms that can even thrive at lower oxygen levels, would be well-supported even in ϵ_2. This highlights the resilience of extremophiles in environments where oxygen availability is far below the thresholds required by other taxa. Their ability to adapt to such minimal oxygen concentrations suggests that microbial life in Europa's ocean could persist, even if oxygen production is limited.

4.4 Comparison with NASA's Juno

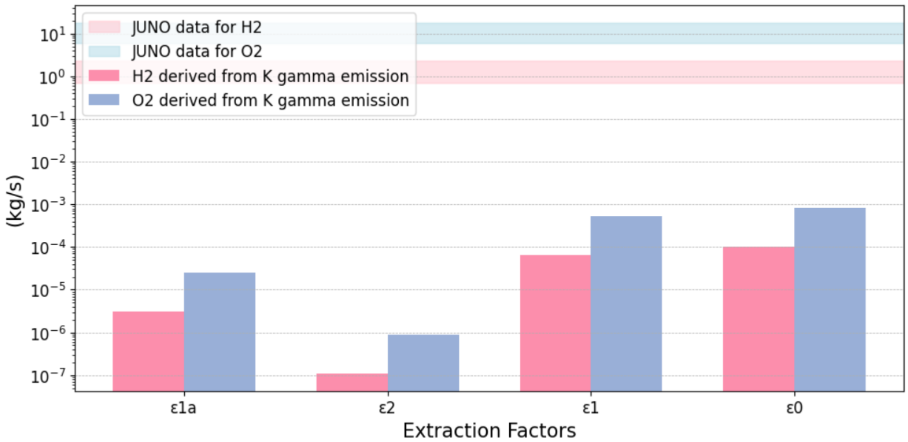

Figure 7: Comparison between amount of H_2 and O_2 derived from ^{40}K γ emission to NASA's Juno observed data.

In all models, the rates are significantly lower than the range observed by NASA's Juno mission, particularly ϵ_2 that focuses solely on the ocean. Despite of that, these results remain significant due to the uncertainties surrounding the transport of oxidants from Europa's subsurface ocean to its surface. The efficiency of transporting these radiolysis productss through the 30-kilometer-thick ice shell is highly uncertain.

More over, on Europa's surface ice, radiolysis is likely dominated by contributions from a mix of radioactive isotopes. ^{40}K is not the only isotope contributing to radiolysis, other isotopes, such as ^{238}U, ^{235}U, and ^{232}Th, also decay, releasing energy through α and β emissions in addition to γ alone. α and β decay are highly ionizing and produce more localized energy deposition in water, driving radiolytic reactions more efficiently.

5 Conclusion

Through this project, we have explored the production of molecular hydrogen (H_2) and oxygen (O_2) in Europa's ocean through radiolysis and radioactive decay, focusing on the contributions of ^{40}K γ emission. We address three key questions: (1) How much oxygen can be produced through ^{40}K γ emission in Europa's ocean? (2) How do different environmental factors affect radiolytic oxygen production? (3) What are the implications for Europa's potential habitability?

Results show that the ^{40}K γ emission contribute a measurable but minor amount compared to the overall production of H_2 and O_2 measured by NASA's Juno mission. This significant discrepancy underscores the contribution of the β decay of ^{40}K itself, which was not considered here, as well as other isotopes, such as ^{238}U, ^{235}U, and ^{232}Th, which decay via alpha and beta emissions. These isotopes release energy more efficiently, driving additional radiolytic reactions that contribute to higher production rates. External sources, such as radiolysis driven by Jupiter's magnetospheric radiation, also likely contribute to the chemical processes on Europa's surface.

Potassium distribution and extraction efficiency significantly influence the oxygen production. Comparisons of calculated oxygen concentration to sublethal oxygen thresholds of Earth's benthic marine organisms show that in the most favorable factors with high potassium availability (ϵ_0 and ϵ_1), oxygen levels could support even complex, oxygen-demanding organisms. In more conservative models, oxygen levels would primarily sustain simpler, highly tolerant organisms, limiting potential ecosystem complexity. This suggests that Europa's habitability strongly depends on potassium availability and the efficiency of oxidant transportation.

These finding underscores the role of radiolytic processes in shaping Europa's chemical environment and its potential to sustain life. While ^{40}K decay provides a steady long-term source of oxygen, it must be considered alongside other isotopes and radiation sources to fully understand Europa's habitability.

Looking ahead, direct measurements of Europa's surface and subsurface chemical composition by Europa Clipper in the next 5–6 years will be essential for refining our understanding of Europa's chemical environment, determining the transport of radiolysis products into the subsurface ocean, and assessing its potential for life. This mission's findings will refine current models and improve our understanding of how radiolysis shapes the habitability of icy moons. Ultimately, this project serves as a stepping stone for exploring the potential for life in other water-rich environments and contributes to our broader understanding of habitable environments on Ocean Worlds.

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