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

By:
Duong Thu Phuong, Nguyen Quang Huy, Nguyen Thuy Linh

under the supervision of Dr. Truong Tuan Ngoc (SwRI, US)

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Introduction

Figure: Earth. *Credit: NASA.*

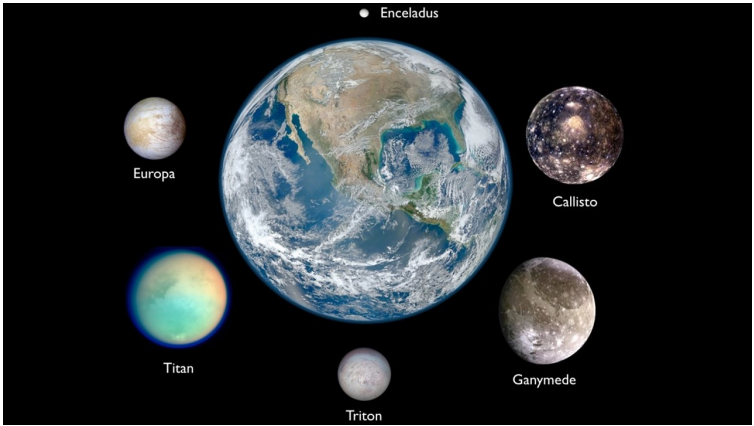
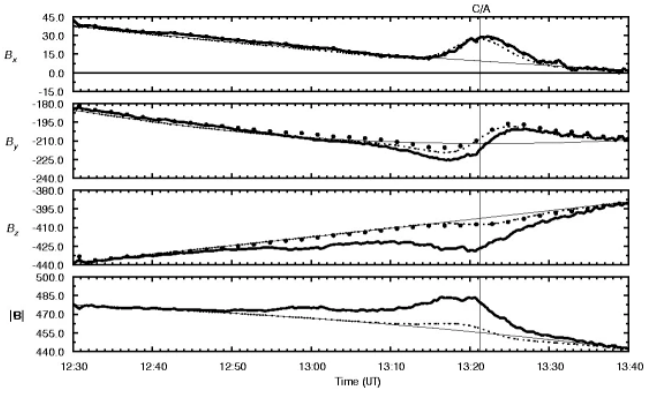


Figure: Some Ocean Worlds. *Credit: Schmdit Ocean Institue.*

Wherever there is liquid water, we found life.

Why Europa?



x	-9.84	-8.17	-6.56	-4.95	-3.31	-1.65	0.04	1.75
y	8.06	6.16	4.34	2.51	0.67	-1.16	-2.96	-4.72
z	0.28	0.31	0.34	0.37	0.39	0.41	0.42	0.43
R	12.72	10.24	7.87	5.56	3.40	2.06	2.99	5.05

Figure: Jupiter's disrupted magnetic field around Europa's space, measured by Galileo spacecraft. *Credit: K. K. Khurana. 1998*

→ **Global ocean of salty water**

Why Europa?

Figure: Portrait of Europa taken by Galileo spacecraft in late 1990s. *Credit: NASA/ JPL-Caltech/SETI Institute*

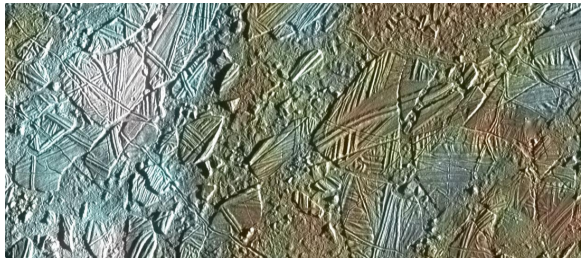


Figure: Zoom in. *Credit: NASA/JPL/University of Arizona*

Can Europa's ocean support life?

What life needs?

- On Earth, oxygen is a primary oxidant used in cellular respiration to generate ATP.
- In the absence of oxygen, alternative oxidants can also support energy production, particularly in extreme environments.

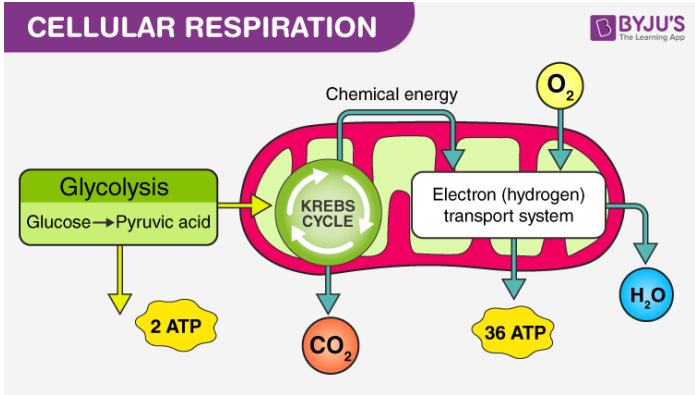


Figure: O_2 breaks down nutrients to release energy. *Credit: BYJU'S.*

Life on Europa?

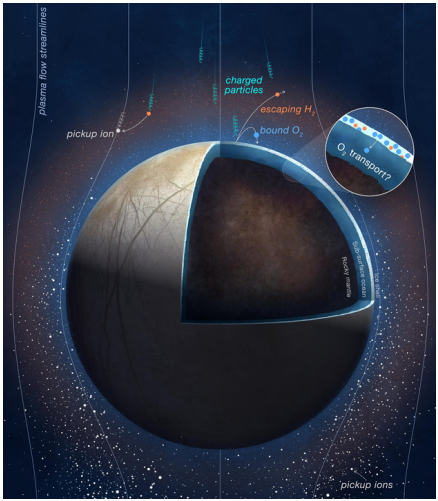


Figure: O_2 production on Europa. *Credit: NASA/JPL-Caltech/SwRI/PU*

- Current idea: Surface radiolysis produce oxygen.
- But how about **30km thick ice shell**??

Water radiolysis

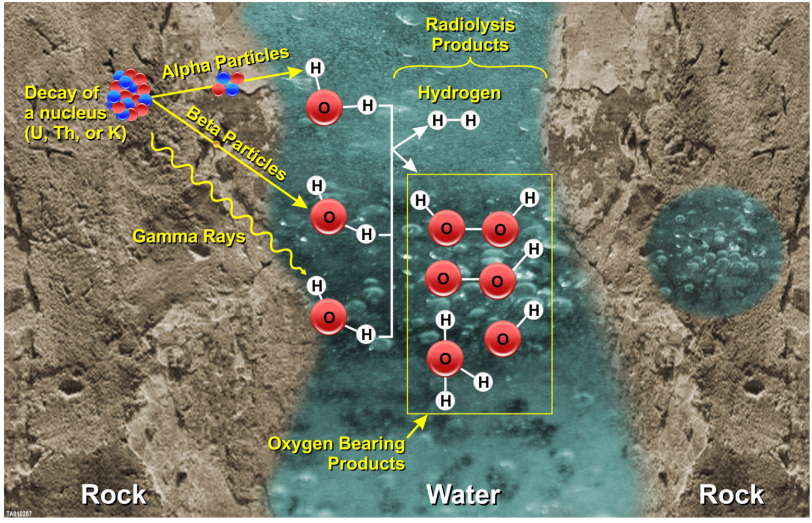


Figure: In-situ O_2 production. *Credit: Alexis Bouquet, 2017.*

Water radiolysis

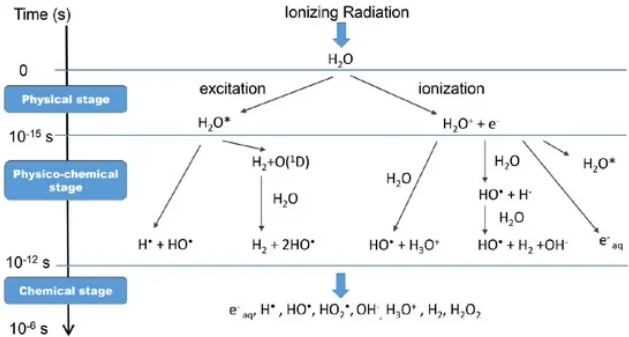


Figure: Events in the radiolysis of water. *Credit: Digby D. Macdonald, 2021*

Table: Some reactions lead to O_2 formation.

No.	Reaction
1	$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$
2	$HO_2 + H_2O_2 \rightarrow O_2 + OH + H_2O$
3	$OH + HO_2 \rightarrow O_2 + H_2O$
4	$OH + O_2^- \rightarrow O_2 + OH^-$
5	$HO_2 + O_2^- \rightarrow O_2 + HO_2^-$
6	$O_2^- + O_2^- \rightarrow O_2 + HO_2^- + OH^-$
7	$O_2^- + H_2O_2 \rightarrow O_2 + OH^- + OH$
8	$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2$

Molecular oxygen is not formed as a primary product of water radiolysis, but appears via secondary reactions.

Main questions

- How much oxygen can be produced through γ emission of 40K decay in Europa's subsurface ocean? Is it significant?
- What are the implications for Europa's potential habitability?

Model setup

40K decay

$^{40}\mathrm{K} \rightarrow^{40} \mathrm{Ca} + \beta$ (89%)
$^{40}\mathrm{K} \rightarrow^{40} \mathrm{Ar} + \gamma$ (11%)

Energy of the γ photon emitted during the decay of 40K into 40Ar

$E_\gamma = \Delta m \cdot c^2$
$\rightarrow E_\gamma = (39.964008 amu - 39.962384 amu) \cdot c^2$
$\rightarrow E_\gamma = 1.5 MeV$

Note that: 1 amu = 931.478 MeV

Model setup

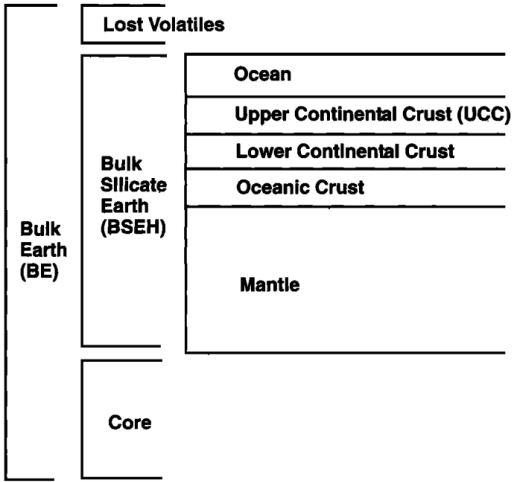


Figure: Geochemical redistribution on Europa (Zolotov and Shock, 2001)

Assumptions:

- Europa's silicate mantle have a composition similar to carbonaceous chondrite meteorites.
- Thermodynamics processes are similar to Earth.

Model setup

Redistribution of 40K on Europa

ϵ_0: Total extraction factor
ϵ_1: Partial extraction factor
ϵ_2**: Ocean-only factor**
ϵ_{1a}: Refined model derived from ϵ_1 and adjusted based on observed Na/K ratios in Europa's atmosphere (M. Brown, 2001)

Assumption: Ratio of radioactive potassium to total potassium is constant and similar to Earth's $\sim 0.0119\%$ *(Brian D. Amiro, 2003).*

Discussion

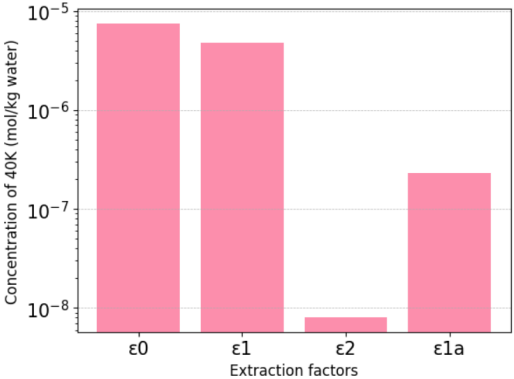


Figure: Molality concentration of 40K.

- ϵ_2's low values $\rightarrow$ inefficiency of direct potassium transport from ocean $\rightarrow$ **most 40K remains trapped in the crust or mantle**.
- ϵ_{1a}: **atmospheric Na/K ratios** may provide a **better proxy** for estimating potassium contributions to the ocean.

Discussion

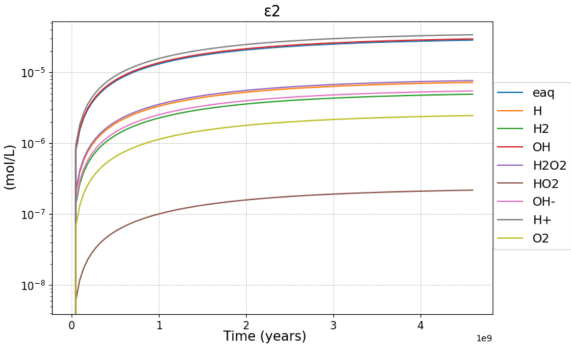


Figure: Concentration of some radiolysis products.

- Most abundant: H^+, OH, H_2O_2, OH^-, ...
- H_2 and O_2 are less abundant but still significant due to **their role as sources for potential life**.

Note that: assume steady-state conditions, do not account for dynamic processes.

Thresholds for microbial survival

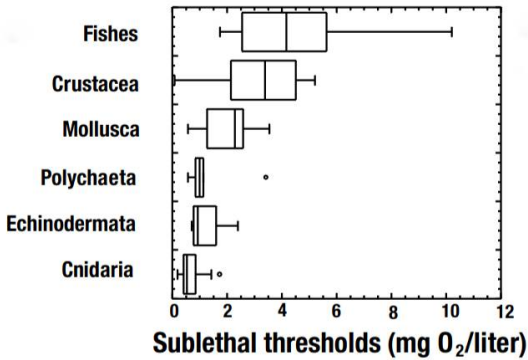


Figure: Distributions of O_2 thresholds among marine benthic communities. *Credit: Raquel Vaquer-Sunyer, 2008*

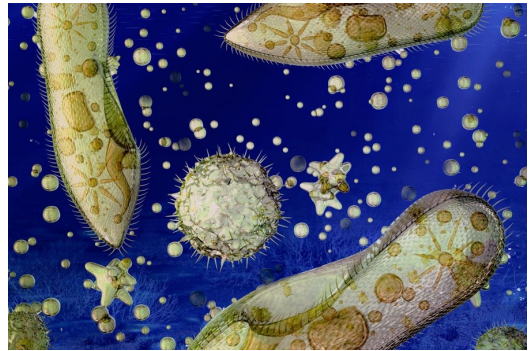


Figure: MIT oceanographers have found that some extremophiles, mostly bacteria in OMZs, have a surprisingly low limit of O_2 needed. *Credit: MIT News*

Discussion

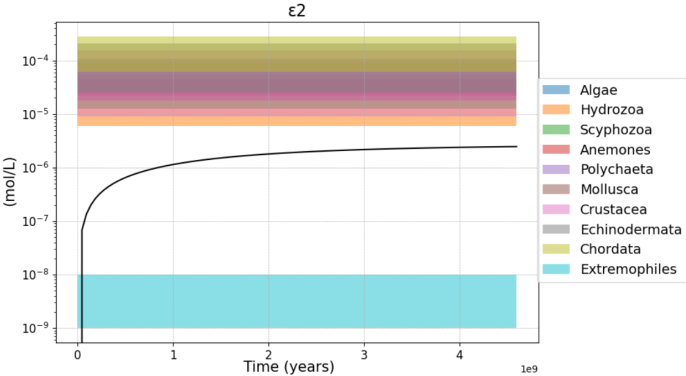


Figure: Comparison of O_2 generated with sublethal oxygen concentrations of benthic marine organisms and extremophiles.

Speculation:

- Extremophiles' ability to adapt suggests that microbial life in Europa's ocean can persist.
- More favorable conditions would be needed for more complex organisms.

→ **Potential significance** of Europa in sustaining life.

Discussion

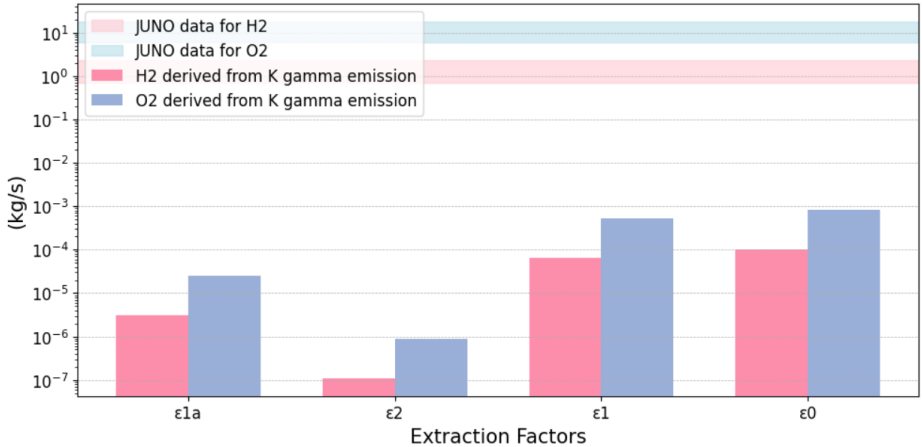


Figure: Comparison between amount of H_2 and O_2 derived from γ emission of 40K decay and NASA's Juno observed data on Europa's surface ice.

Main questions

How much oxygen can be produced through γ emission of 40K decay in Europa's subsurface ocean? Is it significant?

- The γ emission of 40K decay contribute a **measurable** amount of oxygen in Europa's ocean but **minor** compared to the overall production on surface measured by NASA's Juno mission.
- **Yes**, it is significant.

What are the implications for Europa's potential habitability?

- Europa's ocean **may** have the necessary chemical conditions for life, though further data is needed to confirm this hypothesis.

Conclusion

Key takeaways:

- Only 11% of potassium's decay pathway results in gamma-ray emission.
- 40K provides a long-term oxygen source, but must be analyzed alongside other isotopes such as 238U, 235U, 232Th to fully understand Europa's geochemistry.
- Extremophiles' ability to adapt suggests that microbial life in Europa's ocean **can** persist.
- This highlights the potential significance of in-situ radiolytic processes as an alternative pathway for oxygen production, a topic that warrants further study.
- Future research Europa Clipper (next 5–6 years) with direct Europa measurements helps refine models and improve our understanding of life beyond Earth.

Thank you!

Contact information:
duongphuong2109@gmail.com
+84 963 255 788