Estimating the potential of ionizing radiation-induced radiolysis for microbial metabolism in terrestrial planets with rarefied atmospheres

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Abstract

Ionizing radiation is known to have a destructive impact on biology by causing damage to the DNA, cells, and production of Reactive Oxygen Species (ROS) among other things. While direct exposure to high radiation dose is indeed not favorable for biological activity, ionizing radiation can, and in some cases is known to produce a number of biologically useful products. One such mechanism is the production of biologically useful products via charged particle-induced radiolysis. Energetic charged particles interact with surfaces of planetary objects such as Mars, Europa and Enceladus without much shielding from their rarefied atmospheres. Depending on the energy of said particles, they can penetrate several meters deep below the surface and initiate a number of chemical reactions along the way. Some of the byproducts are impossible to produce with lower-energy radiation (such as sunlight), opening up new avenues for life to utilize them. For each of these cases, we calculate the energy deposition rate as a function of depth, and estimate the energy availability for potential metabolic activity. We discuss various mechanisms through which life could support itself utilizing the byproducts of these ionizing radiation-induced reactions, such as chemoautotrophs using solvated electrons, extracellular electron transfer, and indirect electrophory to facilitate processes like carbon fixation, nitrogen fixation and sulfate reduction, and possibly for ATP production.

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1. Introduction

Solar radiation is the primary source of energy for many living organisms on Earth which consists of photons with the energy of a few electron volts. The Sun is also capable of generating an enhanced flux of more energetic X-rays, gamma radiation, and energetic particles (SEPs or Solar Energetic Particles) in extreme events such as flares and Coronal Mass Ejections (CMEs). Additionally, energetic charged particles with much higher energy ($\sim 10^9$ to $10^{21}$ eV), known as Galactic Cosmic Rays (GCRs) are a continued source of radiation throughout our Galaxy. This energetic radiation, which is easily capable of reaching the surface of terrestrial planets with rarefied atmospheres, has enough energy to ionize atoms and molecules (Griffey, 2021). Ionizing radiation is known to have a destructive influence on biology through mechanisms such as the degradation of DNA, production of harmful radicals and the damage of other biological molecules inside the cell (Wu, 1999). Much of the literature is focused on humans being exposed to ionizing radiation and developing diseases due to the disruption of basic biological processes. This can include different kinds of cancer, heart problems, affections on the central nervous system, birth defects, and reproductive challenges (Drago-Ferrante et al., 2022; Ray, 2017; Lim, 2015). Moreover, GCRs are seen as one of the principal obstacles in achieving long-duration interplanetary crewed missions, such as missions to Mars (Chancellor, 2014).

However, microbial life is highly resilient, and can not only withstand high levels of radiation dose, but some species of microbes are known to thrive in high-radiation environments (Gabini et al., 2013; Lin et al., 2005; Chivian et al., 2008). All photosynthetic organisms depend on non-ionizing radiation and absorb the energy from solar radiation by chlorophyll, which is capable of absorbing a wide range of light wavelengths, including in the lower-wavelength, higher-energy ultraviolet (UV) band (Björn et al., 2009). Many organisms susceptible to UV radiation have developed mechanisms such as an increase in the production of melanin in order to counteract high radiation dose (Brenner and Hearing, 2008). Superoxide dismutases, catalases, peroxidases, and oxidases, also serve as bacterial defense mechanisms against destructive reactive oxygen species (ROS) created by radiolytic reactions (Boriso, 2021).

Moreover, ionizing radiation has become quintessential for some organisms here on Earth. Microbial communities have been found to use hydrogen ($H_2$) as a source of energy, obtained as a product of the radiolysis generated by the decay of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ in deep caves (Lin et al., 2005). *Candidatus Desulfurudis audaxuiator*, the first single-species ecosystem discovered in a South African gold mine, powers its metabolic activity using the products of radiation from the decay of uranium, such as $\text{HCO}_3^-$, $\text{SO}_4^{2-}$ and $\text{H}_2$ (Chivian et al., 2008). Although many living things on Earth protect themselves against direct exposure to UV radiation, there is a possibility that high energy radiation sources
could provide a power outlet for life instead of destroying it (Atri, 2016, 2020; Adam et al., 2021).

Ionizing radiation leads to a series of reactions producing radicals, while also generating compounds not usually synthesized under lower energy conditions (Materese et al., 2015). Radiolytic products can catalyze thermodynamically unfavorable reactions needed for the synthesis of organic molecules. It has been demonstrated that radicals can lead to the extremely efficient synthesis of macromolecules from interactions with geochemical substrates such as CO$_2$, H$_2$O, N$_2$, NaCl, chlorapatite and pyrite (Adam et al., 2021). For instance, ionizing radiation may have aided in the production of a number of cofactors such as iron-sulfur clusters, a foundational component of proteins involved in metabolic functions in nearly all organisms (Bonfio et al., 2017). Moreover, radiolysis and subsequent radical reactions are also involved in a host of dimer, oligomer and polymer syntheses important to biomolecule formation (Ghobashy, 2018). It is important to not dismiss the possibility that high energy radiation sources such as GCRs could provide a power outlet for life instead of destroying it under the right circumstances (Atri, 2016; Adam et al., 2021).

While radiolysis powered life may be useful for uncovering life in desolate places on Earth, understanding this type of high energy dependent life may be especially useful in expanding the search for life on potentially habitable planets. The scope of habitable planets includes a goldilocks zone of energy sufficient to power life and to ensure some sort of liquid ocean or sea. Life is more likely to originate in liquid due to the fluidity of the reactionary molecules, the ability for biolayers to organize themselves, the management of complex organic chemical reactivity, and a high availability of solvents (McKay, 2014). Marine environments can also act as a powerful buffer for organisms by aiding in the dispersal of energy. Sources of ionizing radiation include UV rays from the host star, galactic cosmic rays, and even water radiolysis from natural radioactivity within the ocean itself. Here on Earth, bacteria have been found to survive off water radiolysis in continental aquifers deep below the surface (Marie-Françoise, 2004) and sustained in sediments through the catalysis of radiolytic H$_2$ (Sauvage, 2021). If the high energy of ionizing radiation is dispersed or utilized under the correct circumstance, it may be utilized as a possible energy source while also providing extremely favorable circumstances for the synthesis of biomolecules. Evaluating the different possibilities of ionizing radiation as a source of energy in liquid environments could inevitably expand the search for alien life and help us better understand the boundaries of life itself.

2. Ionizing radiation-induced radiolysis as an indirect energy source for life
Water radiolysis is defined as the disintegration of water molecules due to ionizing radiation (Le Caër, 2011). When ionizing radiation comes into contact with a water molecule, the incident energy is enough to excite or ionize the water molecule, forming very reactive ionic or radical species in the process (Altair et al., 2018). Equation 1 shows the primary products of water radiolysis (Le Caër, 2011).

\[
\text{H}_2\text{O} \xrightarrow{\text{ionizing radiation}} \text{H}_3\text{O}^+ + \text{H}_2\text{O}^* + e^- \quad (1)
\]

After the initial ionization, a series of subsequent reactions take place. The ionized water molecule (H$_2$O$^+$) quickly reacts with surrounding water molecules to form H$_3$O$^+$ and HO$•$; the excited water molecule (H$_3$O$^*$) dissociates into HO$•$ and H$•$; and the electron (e$-$) turns aqueous upon hydration (Le Caër, 2011). The products listed above react with one another to form various species, such as OH$^-$, H$_2$O$_2$, and H$_2$. Overall, water radiolysis can be summarized by Equation 2:

\[
\text{H}_2\text{O} \xrightarrow{\text{ionizing radiation}} \text{HO}•, \text{H}•, \text{H}_2\text{O}^+, \text{OH}^-, \text{H}_2\text{O}_2, \text{H}_2, \text{e}_{(aq)} \quad (2)
\]

In an extraterrestrial case of water radiolysis, the ionizing radiation is sourced from either the charged particles in GCRs, the UV light emitted by the host star, or the radioactive energy released by unstable nuclei. For example, on the Jovian moon Europa, water radiolysis is commonly proposed to happen in any of three ways: from GCR-induced ionizing radiation, from the influx of charged electrons accelerated by Jupiter’s nearby magnetic field, or from the decay of radioactive isotopes evidenced to exist on Europa’s subsurface ocean floor (Hand et al., 2007; Altair et al., 2018).

The Jovian icy moons, especially Europa, are the focus of much extraterrestrial water radiolysis research due to their proposed subsurface oceans. These oceans may have the potential to foster life, a possibility made even more promising by the energy availability and chemical disequilibrium evidenced to exist on Jovian moons Enceladus, Europa, Ganymede, and Callisto (Altair et al., 2018). A recent study targeted Europa’s ocean as having strong potential for habitability based on the substantial energy provided from radioactive decay of $^{238}$U, $^{232}$Th, and $^{40}$K (Altair et al., 2018). Oxidized byproducts of water radiolysis, mainly sulfur and iron, could provide energy for sulfur-reducing bacteria to exist in Europa’s ocean (Altair et al., 2018). While the oxidized byproducts of water radiolysis can likely provide enough energy for sulfur-reducing bacteria to survive in extraterrestrial climates, the primary products of water radiolysis, mainly solvated electrons, also have the potential to sustain extraterrestrial life.

The role of electrons is of prime importance in biology by harvesting and transferring energy. Energy is obtained from light by photoautotrophs and can be harvested from inorganic chemical bonds by chemolithotrophs. In both instances, the
transfer and cascade of electrons allows for the retention of energy by a living organism. This energy can then be used to fix carbon to be utilized for long term energy retention, and hence a metabolism (Stelmach et al., 2018). It has also been proposed that a form of chemoautotrophs commonly known as electron-eating bacteria can survive in a variety of different planetary environments in our solar system using the primary products of water radiolysis, specifically solvated electrons, as a direct source of energy (Stelmach et al., 2018). Another important role of electrons is their participation in reduction and oxidation reactions in which electron transfers between electron donors and acceptors are especially relevant to biogeochemical cycles. As these cycles evolved, as did microorganisms which soon allowed oxygen to accumulate in the atmosphere, a key element to the development of complex forms of life (Falkowski and Godfrey, 2008). Additionally, solvated electrons can participate in the production of organic molecules, such as carboxylic acids, aldehydes, alcohols, among others, like ammonium and amines. These molecules are relevant due to the formation of sugars, amino acids, and peptides under favorable conditions and concentrations (Getoff, 2014).

Solvated electrons are one of the primary products of water radiolysis. They are formed in a two-step process described sequentially by Equations 1 and 2. Ionizing radiation initiates the sequence by ionizing a water molecule, which subsequently releases an electron and forms an ion. This free electron can be readily captured by the surrounding liquid water molecules and is therefore termed a solvated electron. Solvated electrons, also known as hydrated electrons if the solvent is liquid water, are formed locally at the site of ionization (Wang, 2018). Although there is still much to be discovered about solvated electrons and their production via water radiolysis, solvated electrons show promise in potentially being a source of energy for deep-sea extremophiles such as the *Shewanella* and *Geobacter* bacteria.

In order to introduce a mechanism of how microbes may be able to use solvated electrons as a direct source of energy, the structure of electron-eating bacteria must be briefly summarized and further extrapolated upon in Section 4. Recent research has identified certain microorganisms, coined “electron-eating bacteria,” as capable of harvesting electrons from solid materials, such as minerals and metals, for energy. Microbes such as those belonging to the *Geobacter* and *Shewanella* genus are able to engage in extracellular electron transfer (EET), a mechanism by which they can accept or donate electrons from surrounding minerals and metals such as iron or copper (Tanaka, 2018). These microbes are able to engage in EET due to either (i) direct electron transfer via certain redox-active proteins (Tanaka, 2018) or (ii) indirect electron transfer via microbial catalysts (Tremblay, 2017). Some microorganisms, typically belonging to the Shewanella family, are able to participate in EET using a combination of both methods (Yang, 2017).

EET via redox-active proteins is one of the more common methods of electron transfer. Outer membrane c-type cytochromes in particular are gaining recognition as the
main redox-active protein involved in EET for electron-eating bacteria (Tanaka, 2018). Alternatively, typical electron shuttles for EET via microbial catalysts include small, soluble compounds such as H₂, formate, ammonia, or Fe²⁺ (Tremblay, 2017). These shuttles work as mediators between the solid electrode and microbe; they transport electrons from the former to the latter.

The mechanisms that define the extracellular transfer of electrons between a microbe and a solid surface can also support hypotheses about the proposed process of direct electron uptake. In contrast to EET, where mineral-reducing bacteria take electrons from the minerals and metals around them, direct electron uptake could bypass the need for a solid electrode entirely. Certain *Geobacter* bacteria are evidenced to have electrically conductive filaments, termed “bacterial nanowires,” that are composed of the cytochromes OmcS and OmcZ (Gu, 2021). These electrically conductive protein nanowires are located on the surfaces of bacteria and aid the cell in transferring electrons to an electron acceptor, essentially acting as reducing agents. Direct electron uptake would be beneficial in environments where there is evidence of water radiolysis to produce an ideal “feeding ground” for the bacteria - a stream of solvated electrons.

Several other probable ways for an organism to survive in extraterrestrial climates under high energy radiation, such as through fluorescence, Förster resonance energy transfer (FRET), or electron transport chains, are discussed in Section 4. For any of these mechanisms to work, a continued source of ionization needs to be present. In the next section, we calculate the rate of ionization, and charged particle-induced energy availability in various planetary objects in the Solar System from the high energy source of GCRs.

### 3. Estimating Energy Availability from Charged Particles on Planetary Objects

When a flux of high energy particles in the form of galactic cosmic rays (GCR) strikes an icy surface, there is a release of electrons from the atoms of that solid as a result of the transfer of energy, creating solvated or “secondary” electrons. These electrons can travel freely within the ice layer at a much lower energy than their cousins of high energy particles in GCR. As we have described earlier, a current of these electrons can be captured by microorganisms living beneath the layer in order to sustain biological growth in a process called direct electrophy (Stelmach et al., 2018). By analyzing the physics of the generated current densities (current per area) giving particle fluxes and the composition of the ice layer, approximations can be made about the minimum amount of biomass that can be sustained, an approximation of the amounts of ATP that can be
produced, and whether that can be plausible for life to exist. This paper specifically analyzes the environments of Europa, Mars, and Enceladus.

GCR-induced radiation dose as a function of depth was obtained from earlier numerical modeling work for Mars (Atri, 2020), Europa (Nordheim et al., 2019), and Enceladus (Teodoro et al., 2017) and are shown in tables 1-3. These tables compare how the dose rates, in units of energy per mass per time, vary as a function of depth into the surfaces of their respective planetary objects. The dose rate can be easily converted to an energy per unit length that will be useful in calculations later in this paper by multiplying by the density of the surface and dividing by the flux of the GCR. Other possible sources for high energy flux can come from electrons, which are the main source of flux on Europa for example. It is also theorized that a high energy electron flux could be created from $\beta^-$ decay of certain radioactive elements, which could possibly sustain biological functions on planets/moons that do not have a high ambient flux from a magnetosphere.

High energy particles in the keV-MeV range that strike an ice layer, transfer their energy to the atoms of the ice to liberate secondary electrons of a much lower energy (1-10 eV). The number of secondary electrons that are created is dependent on the initial energy of the primary particle and the chemical composition of the ice. The equation defining these parameters is given by (Stelmach et al., 2018):

$$n(x) = \frac{1}{\varepsilon}(dE/dx)$$

Where $\varepsilon$ is the energy needed to liberate one secondary electron from the material, averaging around 25 eV, and $dE/dx$ is the energy dissipated from the primary particle per unit length in the ice. $dE/dx$ is derived from the relative dose rate graphs for each body, as described in the previous section using the density and flux. Since a full integration of the graphs was not possible to do without a full dataset, a plot analysis tool was used to approximate the function at various depths, which can be seen in the depth columns of the tables. When the amount of secondary electrons produced is calculated, a current density can be determined given the GCR flux. Current is defined as the flow of electricity (electrons) over time and a current density is that flow over a defined area in Amperes per square area ($A/cm^2$). When the depth, secondary electron flux, and GCR flux are multiplied, the result is:

$$(mm)(particles/mm)(particles/cm^2/s) = particles/cm^2/s$$

Electrons have an elementary charge that can be converted to units of Coulombs ($1 e = 1.60217733 \times 10^{-19} C$), and with an Ampere being defined as $A = C/s$, the equation can be converted into current per area as seen in the tables.
To support the biochemical reactions within microorganisms, a sufficient amount of current (electrons) is needed for reduction processes such as for the proton pump in photosynthesis. Given the current density calculated using the process above, another equation can be used to determine an approximate minimum amount of biomass that the current can sustain. That equation is given by (Stelmach et al.; Seager, Bains, Hu):

\[ \Sigma_B \leq -J \cdot E / P_{me} \]

Where \( \Sigma_B \) is the minimum biomass \((g/cm^2)\), \( J \) is the current density already defined, \( E \) is the electrochemical potential of a reaction that is an attribute of the chemical reaction utilized (carbon fixation was used for this paper), and \( P_{me} \) is defined as the minimal energy rate needed to sustain active biomass, given by:

\[ P_{me} = A \cdot \exp(-E_a/RT) \]

Where \( A \) is a constant, \( E_a \) is the activation energy, \( R \) is the gas constant, and \( T \) is the temperature. The values derived assume an anaerobic environment which fixes \( A \) to a value of 2.2 \( \times 10^7 \) kJ \( g^{-1} \) \( s^{-1} \).

The processes described above utilize the method of direct electrophy in which secondary electrons are directly absorbed by microorganisms. There also exists another phenomenon known as indirect electrophy that involves many of the processes of direct electrophy, except for the mechanism by which secondary electrons impart their energy (Stelmach et al., 2018). Secondary electrons of a slightly higher energy (~30 eV) reach the layer of the microorganisms that also contains a substrate such as a gas. The secondary electron imparts its energy to the electrons in the atom/molecule, which elevates them to a higher orbital level. As the electrons relax to their stable ground states, the energy is converted into light which can be absorbed by microorganisms as part of a photosynthetic reaction. No calculations were performed for this method in this paper but could be readily studied by extending the direct electrophy method to include photon emission.

Adenosine triphosphate (ATP) is used by all living organisms as the main molecule for transportation of the chemical energy required for many of the metabolic reactions that are required for sustaining cells. Deng et al. (2021) estimated for Escherichia coli that during lag phase, \( 0.4 - 4 \times 10^6 \) of ATP molecules are being consumed per cell per second, whilst during the exponential the rate of consumption kept with a value of \( 6.4 \times 10^6 \) ATP cell\(^{-1} \) \( s^{-1} \). In this paper we estimate how much ATP could be produced taking into consideration the energy proportioned by secondary electrons if they enter the electron transport chain to obtain chemical energy. Estimations for how many ATP molecules that can be produced can be determined by utilizing the flux and energy of the secondary electrons that hypothetical microorganisms can use under the surface. The average energy to attach the last phosphate to ADP to produce ATP is 0.304 eV (Atri, 2016). The secondary electron flux can be calculated by multiplying the depth, primary
flux, and secondary electrons per mm, with the energy of the secondary electrons being between 1-10 eV averaging at 5eV in the following equation:

$$\text{ATP Flux} = n(x) \times \phi \times x \times 5 \, eV / 0.304 \, eV$$

Where $n(x)$ is the secondary electron flux, $\phi$ is the GCR flux, and $x$ is the depth. This gives a value for the amount of ATP produced per area per second in the surface layer.

Since Mars, and icy moons Europa and Enceladus are widely considered to be prime targets for finding potentially habitable environments, we focus on them and estimate the ionization rates and energy availability for possible metabolic activity. In all cases, we calculate the energy deposition rate as a function of depth. Galactic Cosmic Rays are composed of charged particles of very high energies (10 GeV and above), which are able to produce secondary particles capable of penetrating several meters deep below the surface.

**Mars**

The following data table shows the estimated values for the environment of Mars at various depths in the rock surface. The average GCR flux of Mars is $33 \, cm^{-2} s^{-1}$, with the average density of Martian rock being $2.65 \, g \, cm^{-3}$ (Atri, 2020).

| Deposition Rate (eV/g/s) | Depth (mm) | Secondary Electrons (particles cm$^{-2}$) | Current Density (A cm$^{-2}$) | Biomass (g cm$^{-2}$) | ATP (cm$^{-2}$s$^{-1}$) |
|-------------------------|------------|------------------------------------------|-----------------------------|------------------------|-------------------------|
| $10^7$                  | 1          | $3.21 \times 10^4$                       | $1.70 \times 10^{-13}$      | $2.78 \times 10^{-10}$ | $5.28 \times 10^{13}$  |
| $1.17 \times 10^7$     | 200        | $3.76 \times 10^3$                       | $3.97 \times 10^{-12}$      | $6.51 \times 10^{-9}$  | $1.45 \times 10^{14}$  |
| $1.46 \times 10^6$     | 400        | $469.0$                                  | $9.92 \times 10^{-13}$      | $1.63 \times 10^{-9}$  | $4.50 \times 10^{12}$  |
| $6.76 \times 10^6$     | 600        | $2.17 \times 10^3$                       | $6.89 \times 10^{-12}$      | $1.13 \times 10^{-9}$  | $1.45 \times 10^{14}$  |
| $4.69 \times 10^6$     | 800        | $1.51 \times 10^3$                       | $6.37 \times 10^{-12}$      | $1.04 \times 10^{-8}$  | $9.30 \times 10^{13}$  |
| $3.03 \times 10^6$     | 1000       | $973.3$                                  | $5.14 \times 10^{-12}$      | $8.44 \times 10^{-9}$  | $4.85 \times 10^{13}$  |
| $1.98 \times 10^6$     | 1200       | $636.0$                                  | $4.04 \times 10^{-12}$      | $6.61 \times 10^{-9}$  | $2.49 \times 10^{13}$  |
| $1.30 \times 10^6$     | 1400       | $417.6$                                  | $3.10 \times 10^{-12}$      | $5.07 \times 10^{-9}$  | $1.25 \times 10^{13}$  |
| $8.19 \times 10^5$     | 1600       | $263.1$                                  | $2.23 \times 10^{-12}$      | $3.65 \times 10^{-9}$  | $5.67 \times 10^{12}$  |
| $5.37 \times 10^5$     | 1800       | $172.5$                                  | $1.64 \times 10^{-12}$      | $2.69 \times 10^{-9}$  | $2.74 \times 10^{12}$  |
| $2.85 \times 10^5$     | 2000       | $91.5$                                   | $9.68 \times 10^{-12}$      | $1.59 \times 10^{-9}$  | $8.58 \times 10^{11}$  |

Data for dose rate and depth sourced from Atri, 2020
Europa

| Deposition Rate (eV/g/s) | Depth (mm) | Secondary Electrons (particles \(mm^{-1}\)) | Current Density (A cm\(^{-2}\)) | Biomass (g cm\(^{-2}\)) | ATP (cm\(^{-2}s^{-1}\)) |
|-------------------------|-----------|---------------------------------------------|---------------------------------|---------------------------|------------------------|
| 2.28 \(\times 10^7\)   | 1         | 5.88 \(\times 10^7\)                       | 4.39 \(\times 10^{-14}\)        | 7.20 \(\times 10^{-11}\)  | 2.20 \(\times 10^{13}\) |
| 3.25 \(\times 10^7\)   | 5         | 8.38 \(\times 10^7\)                       | 3.13 \(\times 10^{-13}\)        | 5.13 \(\times 10^{-10}\)  | 2.24 \(\times 10^{14}\) |
| 3.46 \(\times 10^7\)   | 10        | 8.95 \(\times 10^7\)                       | 6.68 \(\times 10^{-13}\)        | 1.10 \(\times 10^{-9}\)   | 5.10 \(\times 10^{14}\) |
| 4.33 \(\times 10^7\)   | 15        | 1.12 \(\times 10^7\)                       | 1.25 \(\times 10^{-12}\)        | 2.06 \(\times 10^{-9}\)   | 1.20 \(\times 10^{15}\) |
| 5.44 \(\times 10^7\)   | 100       | 1.41 \(\times 10^7\)                       | 1.05 \(\times 10^{-11}\)        | 1.72 \(\times 10^{-8}\)   | 1.26 \(\times 10^{16}\) |
| 1.10 \(\times 10^6\)   | 500       | 2.84 \(\times 10^7\)                       | 1.06 \(\times 10^{-10}\)        | 1.73 \(\times 10^{-7}\)   | 2.56 \(\times 10^{17}\) |
| 1.24 \(\times 10^8\)   | 1000      | 3.21 \(\times 10^6\)                       | 2.40 \(\times 10^{-10}\)        | 3.93 \(\times 10^{-7}\)   | 6.56 \(\times 10^{17}\) |
| 1.45 \(\times 10^7\)   | 5000      | 3.75 \(\times 10^6\)                       | 1.40 \(\times 10^{-10}\)        | 2.30 \(\times 10^{-7}\)   | 4.48 \(\times 10^{16}\) |
| 4.24 \(\times 10^5\)   | 10^4      | 1.09 \(\times 10^6\)                       | 8.17 \(\times 10^{-11}\)        | 1.34 \(\times 10^{-7}\)   | 7.62 \(\times 10^{14}\) |
| 3.00 \(\times 10^3\)   | 5 \(\times 10^4\) | 7.72 \(\times 10^5\)                       | 2.88 \(\times 10^{-12}\)        | 4.72 \(\times 10^{-9}\)   | 1.90 \(\times 10^{11}\) |
| 2.53 \(\times 10^3\)   | 10^5      | 6.55 \(\times 10^5\)                       | 4.89 \(\times 10^{-12}\)        | 8.01 \(\times 10^{-9}\)   | 2.73 \(\times 10^{11}\) |

This data table portrays hypothetical values for the environment of Europa. The average GCR flux for Europa is \(4.66 \times 10^{-9}\) cm\(^{-2}s^{-1}\), with the average density of the moon being 3.01 g cm\(^{-3}\) (Nordheim, 2019).

Enceladus

| Deposition Rate (eV/g/s) | Depth (mm) | Secondary Electrons (particles \(mm^{-1}\)) | Current Density (A cm\(^{-2}\)) | Biomass (g cm\(^{-2}\)) | ATP (cm\(^{-2}s^{-1}\)) |
|-------------------------|-----------|---------------------------------------------|---------------------------------|---------------------------|------------------------|
| 2.28 \(\times 10^7\)   | 1         | 5.88 \(\times 10^7\)                       | 4.39 \(\times 10^{-14}\)        | 7.20 \(\times 10^{-11}\)  | 2.20 \(\times 10^{13}\) |
| 3.25 \(\times 10^7\)   | 5         | 8.38 \(\times 10^7\)                       | 3.13 \(\times 10^{-13}\)        | 5.13 \(\times 10^{-10}\)  | 2.24 \(\times 10^{14}\) |
| 3.46 \(\times 10^7\)   | 10        | 8.95 \(\times 10^7\)                       | 6.68 \(\times 10^{-13}\)        | 1.10 \(\times 10^{-9}\)   | 5.10 \(\times 10^{14}\) |
| 4.33 \(\times 10^7\)   | 15        | 1.12 \(\times 10^7\)                       | 1.25 \(\times 10^{-12}\)        | 2.06 \(\times 10^{-9}\)   | 1.20 \(\times 10^{15}\) |
| 5.44 \(\times 10^7\)   | 100       | 1.41 \(\times 10^7\)                       | 1.05 \(\times 10^{-11}\)        | 1.72 \(\times 10^{-8}\)   | 1.26 \(\times 10^{16}\) |
| 1.10 \(\times 10^6\)   | 500       | 2.84 \(\times 10^7\)                       | 1.06 \(\times 10^{-10}\)        | 1.73 \(\times 10^{-7}\)   | 2.56 \(\times 10^{17}\) |
| 1.24 \(\times 10^8\)   | 1000      | 3.21 \(\times 10^6\)                       | 2.40 \(\times 10^{-10}\)        | 3.93 \(\times 10^{-7}\)   | 6.56 \(\times 10^{17}\) |
| 1.45 \(\times 10^7\)   | 5000      | 3.75 \(\times 10^6\)                       | 1.40 \(\times 10^{-10}\)        | 2.30 \(\times 10^{-7}\)   | 4.48 \(\times 10^{16}\) |
| 4.24 \(\times 10^5\)   | 10^4      | 1.09 \(\times 10^6\)                       | 8.17 \(\times 10^{-11}\)        | 1.34 \(\times 10^{-7}\)   | 7.62 \(\times 10^{14}\) |
| 3.00 \(\times 10^3\)   | 5 \(\times 10^4\) | 7.72 \(\times 10^5\)                       | 2.88 \(\times 10^{-12}\)        | 4.72 \(\times 10^{-9}\)   | 1.90 \(\times 10^{11}\) |
| 2.53 \(\times 10^3\)   | 10^5      | 6.55 \(\times 10^5\)                       | 4.89 \(\times 10^{-12}\)        | 8.01 \(\times 10^{-9}\)   | 2.73 \(\times 10^{11}\) |

This data table portrays hypothetical values for the environment of Enceladus. The average GCR flux is \(8.2 \times 10^{-3}\) cm\(^{-2}s^{-1}\), with the average density of the moon being 1.61 g cm\(^{-3}\) (Teodoro, 2017).
4. Energy Acquisition to Life – Case studies and other Possible Mechanisms to Life Dependent on Radiolysis

As mentioned in Section 2, a number of microbial communities have been found to use radiolysis products to power their basic life functions (Blair et al., 2007). One example is Candidatus Desulfurudis audaxviator, a chemoautotrophic extremophilic sulfate-reducing bacteria found in a 2.8 km deep gold mine in the Witwatersrand region in South Africa (Chivian et al., 2008). Since D. audaxviator thrives in an environment completely isolated from the photosphere and generally bombarded with high energy particles from surrounding rock, its metabolic chemistry significantly relies on radicals produced by radiolysis, particularly of water (Atri, 2016). Sequencing of D. audaxviator's genome revealed genes encoding for pathways for sulfate reduction, carbon fixation, and nitrogen fixation, all utilizing excited metabolites or intermediates associated with water radiolysis and, in the case of some carbon fixation pathways, bicarbonate radiolysis (Chivian et al, 2008). The presence of D. audaxviator in underground radiolytic zones implies the ability for self-sufficient life to be powered by processes such as water radiolysis and use said radiolysis for various forms of electron transfer.

In addition to D. audaxviator, there are other microorganisms which use similar means to thrive in radiolytic zones. As previously discussed, subsurface marine sediments can often serve as suitable radiolytic zones for metabolic activity, and may be promising possibilities for life on icy moons such as Europa (Blair et al., 2007; Altair et al., 2008). Analysis has been done for the potential radiolysis of CO₂ ice on Europa’s surface in which Europa’s oceans could hence be oxidized with O₂ concentrations plausibly similar to those in Earth’s oceans (Hand et al., 2007). Prior studies have also highlighted how molecular hydrogen is one of the most likely contenders for electron donors in radiolytic zones (Lin et al., 2005; Blair et al., 2007; D'Hondt et al., 2009; Gregory et al., 2019). Recent studies have studied sediments from the subseafloor near the Juan de Fuca ridge and isolated numerous sulfate-reducing bacteria of genera Desulfoptosporosinus, Desulfotomaculum, Desulfovibrio and Desulfotignum; these bacteria demonstrated chemolithotrophic growth in the presence of H₂ as the sole electron donor and small amounts of organic compounds, with a strain of Desulfovibrio indonesiensis even demonstrating chemolithoautotrophic activity in the absence of organic compounds (Fichtel et al., 2012). Given that H₂ can be produced through water radiolysis and because subseafloor sediments with limited organic compounds can accommodate various sulfur-reducing chemolithotrophs as well as chemoautotrophs, it is quite possible that sulfate-reducing species like Dv. indonesiensis in addition to D. audaxviator could thrive in
isolated deep subseafloor radiolytic zones on other celestial bodies in the Solar System (Fichtel et al., 2012; Altair et al., 2008).

Moreover, chemoautotrophic bacteria fix carbon from inorganic sources for their metabolism. It is especially important to consider the pathways of carbon fixation when determining the likelihood of microbial ecosystems on deep sea sediments in the Solar System due to the impact it may have on influencing carbon cycling and other larger-scale processes in the ecosystem (Molari et al., 2013). While *D. audaxviator* does appear to contain channels to allow for heterotrophic breakdown of sugars and amino acids from dead cells, its genome in particular encodes two carbon monoxide dehydrogenase (CODH) systems which can be used for the reductive acetyl-coenzyme A (CoA) pathway (Wood-Ljungdahl pathway) (Chivian et al., 2008). Notably, methanogens also utilize a form of the Wood-Ljungdahl pathway for their own metabolism, which may be of interest due to competition between sulfate-reducing bacteria and methanogens’ development on surface sediments (Hügler and Sievert, 2011; Maltby et al., 2016). Similar to that pathway, other chemoautotrophs may incorporate processes such as the reductive tricarboxylic acid (rTCA) cycle (reductive Krebs cycle), 3-hydroxypropionate (3-HP) bicycle, 3-hydroxypropionate/4-hydroxybutyrate (3-HP/4-HB) cycle and dicarboxylate/4-hydroxybutyrate (DC/4-HB) cycle to facilitate carbon fixation from inorganic sources and use it for metabolism (Hügler & Sievert, 2011). However, in contrast to these, most chemoautotrophs and photoautotrophs use the Calvin-Benson cycle, which involves using ATP, NADPH and enzymes like RuBiSCO to fix carbon dioxide (Tamoï et al., 2005). Overall, inorganic molecules on other bodies in the Solar System could be used for carbon fixation by microbial communities, with the Wood-Ljungdahl pathway (also used by *D. audaxviator* and other sulfate-reducing bacteria) and the Calvin cycle being likely contenders for inorganic fixation processes in primitive life (Fuchs, 2011; Ward and Shih, 2019). Similar to anoxic environments on Earth today and in the past, it is possible that inorganic carbon fixation on other Solar System bodies takes place with H₂ as a primary electron donor (Tice and Lowe, 2006). Arguably, radiolytic zones in deep sea sediments could facilitate inorganic carbon fixation through water radiolysis, as discussed in earlier paragraphs (Blair et al., 2007; Chivian et al., 2008). Overall, various mechanisms such as carbon fixation, nitrogen fixation and sulfate reduction can be conducted by uptaking solvated electrons and ions associated with radiolysis. We now shift to a discussion surrounding electron transfer. As mentioned in Section 2, there are various mechanisms by which organisms can uptake solvated electrons.

There are, however, other mechanisms which may be possible for an organism to utilize high energy to power its metabolic functions. One said proposition is the excitement of molecules in order to fluoresce (Altair et al., 2018; Stelmach et al., 2018). The fluorescence would give off a light that could then be used by light harvesting mechanisms. Another mechanism that could arise from the excitement of molecules and subsequent release of energy is through the utilization of Förster resonance energy
transfer (FRET) (Jones and Bradshaw, 2019). FRET would allow for the direct transfer of energy from an excited molecule to the receiver. If in close enough proximity (100 angstroms), it would be possible for the excited molecule to directly contribute to the electron transport chain (Beljonne et al., 2009).

Additionally, electrons could be shunted directly to an electron cascade similar to that in photosynthesis (Strümpfer et al., 2012). Overall, photosynthesis dominates net primary production of energy on Earth. By incorporating electron transfer, photosynthesis mediates the production of glucose (chemical energy) from photons (light energy). In general, electron transport chains allow for charge carriers like NADP+, NAD+ and FAD to shuttle incident light or chemical energy and use it to drive metabolic processes within the organism (Ying, 2008). These charge carriers cycle between oxidized and reduced states to facilitate photosynthesis, cellular respiration and myriad additional functionalities, including ROS neutralization (Chandel, 2021; Fernandez-Marcos and Nóbrega-Pereira, 2016).

In terms of radiolysis and determining what primitive microbial life may look like elsewhere in the Solar System, charge carriers can be significant objects of study, especially with regard to iron-sulfur clusters (Wang et al., 2011). As discussed in the Introduction, ionizing radiation-induced radiolysis may have aided in the production of iron-sulfur clusters, which are now found in proteins involved in nearly every known organism’s metabolism (Bonfio et al., 2017). Iron-sulfur clusters have a unique importance in extant biochemistry underscored by their versatility of functionality; these clusters can be responsible for aiding in electron transfer through redox reactions, influencing tertiary and quaternary protein structure and facilitating catalysis (Beinert, 1997). Moreover, iron-sulfur clusters have been shown to be able to reduce NAD+ to NADH in anaerobic prebiotic conditions, which indicates the possibility of radiolytic geochemical syntheses having an influence on abiogenesis (Weber et al., 2022). There are various theories regarding the origin of iron-sulfur clusters on Earth, but particularly relevant to our analysis is the evidence that UV light can induce photooxidation of ferrous ions and photolysis of organic thiols like cysteine to promote formation of polynuclear clusters such as [2Fe-2S] and [4Fe-4S] even in deep submerged environments (Bonfio et al., 2017). However, the availability of UV light in an Iron-Sulfur World has been disputed and conflicts exist regarding the likelihood of such conditions playing out (Wang et al., 2011; Ross, 2008). On a general astrobiological note, it has been suggested that iron-sulfur clusters played a major role in prebiotic conditions that led to primitive life on Earth; Wächtershäuser (1988, 1998) suggested that reactions between iron (II) sulfide and hydrogen sulfide to produce pyrite could have led to important reducing chemistry that predated and facilitated the rTCA and Wood-Ljungdahl pathways for inorganic carbon fixation. The equation for this process can be written as follows:

$$\text{FeS (s)} + \text{H}_2\text{S (aq)} \rightarrow \text{FeS}_2 (s) + \text{H}_2 (g)$$
The above reaction is additionally thermodynamically spontaneous with $\Delta G^\circ = -38.63$ kJ/mol and can be coupled with various nonspontaneous organic reactions; redox reactions of the FeS/S/FeS$_2$ redox system, which includes the above reaction, could have helped facilitate conversions of carboxylic acids to keto-acids as well as the generation of pyruvate from lactate in prebiotic conditions (Wang et al., 2011).

In extant organisms, charge carriers including ferredoxin (which contains iron-sulfur clusters itself) and NADPH have been implicated in promoting iron-sulfur cluster assembly by transferring electrons to a reaction involving a desulfurase to derive elemental sulfur and scaffold proteins to bind it to ferrous ions and another sulfur to create Fe$_2$S$_2$ clusters (Yan et al., 2015). Notably, this mechanism in primates is orthologous to the ISC operon in E. coli, which encodes for a similar process of iron-sulfur assembly (Yan et al., 2015). Moreover, Rieske iron-sulfur proteins, which consist of a [2Fe-2S] cluster exist in some form in prokaryotes as well as eukaryotes, have been shown to exercise important electron transfer activity in cellular respiration (Schmidt and Shaw, 2001). These proteins are incorporated in cytochrome $bc_1$ and $b_6$ $f$ complexes and engage in redox reactions to aid in metabolism, representing further significance and near-universality of iron-sulfur clusters on simple and complex life alike (Schmidt and Shaw, 2001; Wächtershäuser, 1998).

### 5. Conclusion and Discussion

Planets are continually bombarded with radiation and its interaction with matter varies depending on its energy. When it comes to ionizing radiation, its effects are usually associated with harm. It is not surprising considering that its interaction with DNA results in degradation. However, it also has positive outcomes. Its high energy may have helped the formation of prebiotic molecules, and it has been demonstrated that many organisms take advantage of the products of various types of radiation here on Earth. Based on the positive implications from ionizing radiation and on the existence of microorganisms living near to it, we propose a scenario in which an organism can uptake electrons directly from radiolysis in subsurface environments. While ionizing radiation that can create such electrons may be sourced from X-ray, gamma radiation and unstable nuclei, GCRs ought to also be considered as a producer of electrons. GCRs may interact with atmospheres or surfaces generating a cascade of particles that become less energetically charged as they cross the milieu in which secondary electrons are produced. Our hypothesized organism would be able to uptake solvated electrons directly through appendages such as bacterial nanowires. Said organisms would also be able to withstand and convert the high energy of radiation through mechanisms described before or through novel mechanisms unknown to Earth.
We estimated the electron flux at different depths of the surface bodies; Mars, Europa and Enceladus, in which life is postulated to be due to the presence of water. In the case that all the energy proportioned by electrons was used for the production of ATP, considering that a cell consumes $6.4 \times 10^6$ ATP molecules per second, at a depth of 1 meters below the surface Mars could support $7.58 \times 10^6$, Europa $1.9 \times 10^{12}$ and Enceladus $1.03 \times 10^{11}$ cells. It is also important to note that the ATP consumption can significantly change depending on the type of microorganism and that there may be other sources of energy. It is not the same to compare a very metabolically active bacteria like *E. coli* to an anaerobic bacteria in an energy poor environment, which would be the case for the microorganisms that would arise on those extraterrestrial bodies. Moreover, it is also important to note that solvated electrons may also occur from other sources such as through atmospheric pressure plasmas in contact with liquids (Yashuang et al., 2020).

It is necessary to highlight that certain factors are not included, such as the effect of different temperatures on the calculations and on the possibilities for life to thrive in harsh environments. We also did not consider if the environmental conditions of the selected rocky bodies are appropriate for the emergence of complex organic molecules, such as cytochromes. Additionally, it must be noted that it may be difficult for life to thrive in an electron solvated environment due to its high conductivity. Finally the flux of GCRs on Earth, due to its thick atmosphere and a strong global magnetic field, is not large enough to be a significant factor to life on Earth; therefore we don’t have an example of any life that evolved under such conditions and hence all work proposed is completely theoretical.

While a number of planets considered as prime targets for astrobiology have been explored with flyby missions and orbiters or with landers and rovers such as on the surface of Mars, the shallow subsurface environment is yet to be explored. The shallow subsurface environment is not directly subjected to extreme temperature variations and other harsh conditions. On Mars, for example, shallow subsurface chemistry might be initiated by GCRs and can produce biologically useful products, such as ATP (Atri, 2016). We have calculated the energy deposition rate from GCRs on Mars, Europa and Enceladus and have discussed possible mechanisms through which life could power itself in such conditions. One proposed hypothetical mechanism is direct electrophy of secondary electrons, which we have presented as a continuation of the work done by Stelmach et al. (2018). By assessing the GCR flux on three different planetary environments, we can now have more poignant discussions regarding this theory and its implications for the search for life on environments such as the ones proposed. An interesting example of one of such searches would include the polar caps of Mars. A higher flux of galactic cosmic rays penetrate the surface of Mars due to an absence of a thick atmosphere. These high energy particles could penetrate into the pockets of the polar caps made viscous through high salt content. The carbon dioxide ice surrounding these pockets would allow for an oxidative species to allow for a similar process outlined
by Atri (2016, 2020). Additionally, it has been shown that solvated electrons have the ability to reduce liquid carbon dioxide (Rybkin, 2020), a promising step toward important cycles such as the carbon fixation cycle.

We argue for future planetary science missions to have instruments capable of exploring the shallow subsurface environments of prime astrobiology targets discussed here. A suite of instruments capable of measuring radiation levels, exploring the subsurface chemistry and detecting possible signs of biological activity are needed to assess the possibility of these mechanisms offering support to putative microbial communities in otherwise inhospitable environments.

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