On the possibility of Galactic Cosmic Ray-induced radiolysis-powered life in subsurface environments in the Universe

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Abstract

Photosynthesis is a highly efficient mechanism developed by terrestrial life to utilize the energy from photons of solar origin for biological use. Subsurface regions are isolated from the photosphere, and consequently are incapable of utilizing this energy. This opens up the opportunity for life to cultivate alternative mechanisms in order to take advantage of other available energy sources. Studies have shown that in subsurface environments, life can use energy generated from geochemical and geothermal processes to sustain a minimal metabolism. Another mechanism is radiolysis, in which particles emitted by radioactive substances are indirectly utilized for metabolism. One such example is the bacterium fueled by radiation, found 2 miles deep in a South African mine, which consumes hydrogen formed from particles emitted by radioactive U, Th and K present in rock. In addition to in situ sources in such environments, another source of radiation in the subsurface environments is secondary particles generated by Galactic Cosmic Rays (GCRs). It is a steady source of energy comparable to that produced by radioactive substances, and the possibility of a slow metabolizing life flourishing on it cannot be ruled out. GCR particle-induced radiolysis can produce H$_2$ and other biologically useful products such as oxides and organics. We propose two mechanisms through which GCR-induced secondary particles, which are able to penetrate in subsurface environments, can be utilized for biological use: (1) GCRs injecting energy in the environment through particle-induced radiolysis, and (2) organic synthesis from GCR secondaries interacting with the medium. Laboratory experiments to test these hypotheses are also
proposed. We discuss the implications of these mechanisms on finding life in the Solar System and elsewhere in the Universe.

1. Introduction

Radiation in the form of photons is the primary way by which solar energy is transferred to living systems. The energy of a typical photon is between 2 - 3 eV (Visible Red – 1.8 eV and Visible Blue – 3.1 eV), and an abundant supply of such photons makes it convenient for life to utilize it for metabolic purposes. Ionizing radiation, on the other hand has mostly been associated with health-effects on humans (United Nations Report, 2013; Brenner et al., 2003) and/or studies of radiation resistance on microbes (Mattimore and Battista, 1996; Battista, 1997). By definition, ionizing radiation has the energy to ionize, or to eject at least one electron from a neutral atom or a molecule, which is 13.6 eV for a neutral hydrogen atom, for example. Ionizing radiation can interact with the DNA and cause reparable or irreparable damage, depending on the type and energy of the radiation (Ward, 1988). Such damages have the potential to modify the genetic code through mutations, alter the way the DNA functions, and transfer mutations to the next generation(s) (Dubrova et al., 2000; Dubrova and Plumb, 2002). Radiation damage can also cause cancer as seen in a number of studies with UV and particle interactions with humans, primarily in context of oncological studies, nuclear accidents and astronaut health in outer space (Cucinotta and Durante, 2006; Durante and Cucinotta, 2008, NCRP Report, 2002, 2010). Nevertheless, high dosage of ionizing radiation can force organisms to develop mechanisms that enable them to survive in extreme conditions (Thornley, 1963).

Geochemical processes are well known to support subsurface life (Ghirose, 1997; Fernández-Remolar et al., 2008). An important shift in our understanding came about when studies revealed that subsurface life can be independently supported by radiolysis, where the source of radiation is particles emitted from the decay of radioactive substances (Lin et al., 2005; Onstott et al., 2006). Radioactive materials present deep underground produce secondary particles such as alpha, beta and gamma radiation. Secondary particles interact with the environment and provide energy for chemical change. Organisms can use these particles indirectly for metabolic purposes. *Candidatus Desulfurudis audoxviator* is such an example, which thrives in a
radiolysis-powered ecosystem. Radiation from radioactive rock dissociates H₂O into a number of radicals, useful for biological reactions. It is able to extract carbon from dissolved CO₂ and nitrogen in form of ammonia from the rock, and utilize them to synthesize amino acids. Such an organism can potentially thrive in subsurface environments on Mars, Moon, Europa or other planetary systems in the presence of radioactive substances. 

*Candidatus Desulforudis audaxviator* thrives in a 2.8 km deep South African gold mine (Lin et al., 2006; Chivian et al., 2008). A comprehensive analysis on the availability of nuclear power for deep surface microbes has also been done (Lin et al., 2005). Radiolytic dissociation of water due to radiogenic decay of U, Th and K in rock produces a number of radicals, and generates H₂, along with other biologically useful products. Radiolytically generated chemicals provide the necessary energy and nutrients to the system, sulfate (SO₄²⁻) reduction is the dominant electron-accepting process and H₂ and formate are primary electron donors. A part of the energy is also utilized to repair damage caused by ionizing radiation. Radiolytic H₂ is used by methanogens for abiotic hydrocarbon synthesis (Chivian et al., 2008). It provides them with the energy to sustain a minimal metabolism. Studies have shown that H₂ produced through geochemical processes can be utilized for metabolism, independent of photosynthesis using similar mechanisms (Stevens and McKinley, 1995).

Here, we aim to take this one step further, and propose that instead of in situ radiation sources, the radiation supporting life can be of cosmic origin. Galactic cosmic rays are particles originating beyond the solar system (Gaisser, 1990; Dorman, 2004; Stanev, 2010). They have a lower flux but much higher energy than other radiation sources on the Earth, and have noteworthy biological effects on terrestrial life and possibly on extrasolar planets (Dartnell, 2011; Atri et al., 2013; Atri and Melott, 2014). Secondary particles include electrons, positrons, gamma rays, neutrons and muons. (Gaisser, 1990). Muons can travel several kilometers depending on their energy (Dorman, 2004; Stanev, 2010). Secondary particles can induce radiolysis and as we demonstrate later, possibly power a subsystem ecosystem.

2. Proposed Mechanisms
2.1. Galactic Cosmic Ray-induced radiolysis

As discussed in the previous section, radioactive rocks provide an in situ production source of energy for subsurface life. We propose a similar mechanism, however the energy source that we consider is extraterrestrial. For planets with substantial atmospheres, the primary GCR particles strike the atmosphere and produce a cascade of secondary particles, also referred to as an air shower (Gaisser, 1990). If a planet lacks an atmosphere, particles are able to directly strike the surface and the cascade of secondary particles is able to propagate underground (Mei and Hime, 2006). The secondary particles produced in the cascade, such as pions and kaons, are highly unstable, and quickly decay to other particles including beta particles (electrons and positrons) and gamma-rays. It must be noted that beta particles and gamma-rays are also produced during radioactive decay in underground rock. Muons are produced when charged pions decay, and can travel several kilometers depending on their energy. We emphasize that different types of secondary particles such as electrons and positrons can contribute to radiolysis in regions near the surface but muons become important at greater depths where the flux of other particles becomes nearly zero. They only undergo electromagnetic interactions and lose 2-8 MeV energy per gram per square cm in the material they traverse (Groom et al., 2001). The energy loss is a combination of ionization, bremsstrahlung, pair production and inelastic nuclear scattering (Heisinger et al., 2002).

Energetic particles (including muons) are capable of destroying organic materials present on the surface or subsurface environment of planets with thin atmospheres. A number of studies have been devoted on studying the impact of GCRs on the possible destruction of organic matter on Mars (Pavlov et al., 2012; Pavlov et al., 2002; Dartnell et al., 2007). Mars' surface radiation dose is several orders of magnitude higher than that of the Earth due to a thin atmosphere. High radiation dose also equates to a substantial energy spent in repairing radiation-induced damage. Bacterium Deinococcus radiodurans is the focus of numerous studies and is the most radioresistant microbe with a LD10 at 15 kGy. D. radiodurans have a specialized recombination system for DNA repair from ionizing radiation. Interestingly, many fungal species also have very high radiation resistance. Many fungi have 10% survival chance or LD10 values exceeding 5 kGy. Other species, such as Ustilago
*Maydis* are also known to have extreme radiation resistance but have a different mechanism to cope with. It has been found that the action of proteins is primarily responsible for the repair mechanism (Holloman et al., 2007). Presence of several microorganisms has been studied in the Russian Mir Space Station as well as the International Space Station (Alekhova et al., 2005). An abundance of highly melanized fungal spores in the early Cretaceous period deposits has been uncovered, where other plant and animal species have died out (Hulot and Gallet, 2003). These types of fungi can be found in high-altitude terrains, Arctic and Antarctic regions, and in the Evolution Canyon in Israel.

We propose that a part of the energy deposited by GCRs can be utilized for radiolysis. As the particles traverse in the subsurface medium they lose energy by ionizing it. As we demonstrate later, the ionizing energy produced by secondary particles is comparable to energies observed in radioactive decay processes known to support radiolysis-based life. At greater depths, muons become important because of their long-range as discussed earlier. Muons transfer their large kinetic energy to the medium, and also form Muonium ($\mu^+e^-$), which has been found useful for various chemical and biological reactions due to its similarities with hydrogen (Percival et al., 1978). It should be noted that below 15 km, the energy deposition rate is constant due to contribution from neutrinos.

We use the GEANT4 package to model the energy deposition rate in subsurface environments. It is a widely used package and considered a gold standard in modeling particle interactions. The code models all particle interactions and it traverses through a medium and has been well tested in the planetary science community. We consider two cases here; case 1, an icy planetary object with no atmosphere so the entire GCR flux deposits energy in the ground; and case 2, the Earth where most of the radiation is blocked by the atmosphere. The flux of GCR was taken from Dorman (2004) and incident directly on the planet’s surface in case 1 and on the earth’s atmosphere in case 2. The surface in case 1 is pure ice with 1 g/cm$^3$ density and in case 2 is standard rock with density of 2.65 g/cm$^3$. $10^9$ particles were used for simulations and the energy deposition profile was obtained in each case. Figures 1 and 2 show the subsurface energy deposition rates for cases 1 and 2 respectively. In case 1, the energy deposition rate is $\sim 10^7$ eVg$^{-1}$s$^{-1}$ close to the surface and drops below $10^5$ eVg$^{-1}$
1 s⁻¹ below 8 m depth. The energy deposition rate is about three orders of magnitude lower in case 2 as seen in figure 2. The atmosphere absorbs most of the radiation, however because of the long range of muons, small amount of radiation reaches a depth of a few km.w.e.

Let us now compare these results with the energy environment of Desulforudis audaxviator. The radiolytic model calculations by Lin et al. (2005) yielded the net dosage range of alpha particles between 4.25×10⁵ - 8.52×10⁵ eV g⁻¹ s⁻¹, beta particles between 6.58×10⁴ - 4.27×10⁵ eV g⁻¹ s⁻¹, and for gamma rays between 4.00×10⁴ - 2.25×10⁵ eV g⁻¹ s⁻¹ (Lin et al., 2005). This energy is used to split water molecules into H⁺ and OH⁻ forming H₂O₂. H₂O₂ in turn reacts with the surrounding medium to form sulfate, SO₄²⁻. It uses sulfate instead of O₂ and obtains nitrogen from surrounding ammonia (Lin et al., 2006; Chivian et al., 2008). As one can see, the energy deposition rate is about an order of magnitude higher close to the surface in case 1 than that available to Desulforudis audaxviator.

Life can invent a variety of mechanisms to utilize such large range of energy injected underground. It could produce molecular hydrogen and oxydants useful for life. Muons can both directly react with molecules present in the medium, and also indirectly through radiolysis products (Smilga and Belousov, 1994). A detailed description of all the chemical reactions including the intermediate steps can be found elsewhere (Hatano et al., 2010). Let us now use these radiation doses to calculate familiar biologically useful processes such as the production of ATP. The terminal phosphate bond in ATP requires 0.304 eV per molecule (Schulze-Makuch and Irwin, 2008). As in case of Candidatus Desulforudis audaxviator, the total energy produced by radioactive rocks would be potentially divided between radiolysis-powered metabolism, radiation damage and damage repair, only a fraction of the total energy will be utilized for radiolysis. Based on our simulation results, the upper limit of ATP production in case 1 is ~ 3×10⁷ ATP molecules g⁻¹ s⁻¹ assuming 100% efficiency.

It must be mentioned that life, as we know it, requires water, which is a neutral fluid and fits perfectly with temperature variations on Earth. However, other fluids might offer similar functionality in terms of being stable; provide transportation of essential nutrients and remain liquid for temperature ranges for that particular planet.
Underground water or other fluid sources, in combination with flux of secondary particles can provide a stable self-sustained environment for life to exist. Low energy availability can produce organisms with a very slow metabolism. There is a possibility of an ecosystem thriving on this energy source based on other biochemical bases, and might necessitate alternate approaches to detect life 'as we don't know it' (Schulze-Makuch and Irwin, 2008; Azua-Bustos and Vega-Martínez, 2013) in subsurface environments on Earth and elsewhere.

We propose a laboratory experiment to test this hypothesis. It would involve gradually changing the radiation environment of Candidatus Desulforudis audaxviator, by using different radiation beams, keeping the same chemical environment and observing its growth over a period of time. If the organism is able to adapt to gradually changing radiation environment, it can be eventually exposed to GCR secondaries proving an ultimate test the hypothesis.

### 2.2 GCR-induced synthesis of organics and other biologically useful products

Even though Desulforudis audaxviator is able to maining an ecosystem independent of photosynthesis, it uses photosynthetic products. Hydrotherms on the other hand are thought to be based on chemosynthetic products (Bonch-Osmolovskaya, 2010). Based on experimental results and theoretical models, some authors have proposed that high-energy particles could produce amino acid glycine on extraterrestrial ices (Holtom et al., 2005). We propose that biologically useful products, using a similar mechanism can be produced in subsurface environments by GCR-induced secondaries. Charged particles directly interact with ice and produce a number of biologically useful secondary products (Bernstein et al., 1995; Kobayashi et al., 1995; Hudson and Moore, 1999). Hudson and Moore irradiated different mixtures of water and CO with 0.8 MeV protons at temperatures near 16 K in order to simulate interstellar conditions. The results of isotopic substitution and IR spectroscopy showed the formation of several hydrocarbons such as HCOOH, HCO, H$_2$CO and CH$_3$OH (Hudson and Moore, 1999). Earlier experiments of Bernstein et al. were conducted with a larger temperature range (12 to 300 K), and in addition to the above mentioned products, they discovered hexamethylenetetramine (HMT, C$_6$H$_{12}$N$_4$), ethers, alcohols, compounds related to polyoxymethylene, ketones and amides in their
samples (Bernstein et al., 1995). Their latter experiments showed the formation of aroma-bearing ketones and carboxylic acid functional groups (Bernstein et al., 2003). Other groups have also reported experimental evidence of the formation of amino acid precursors on exposure to high-energy particles (Kobayashi et al., 2000; Kobayashi et al., 2001). Kobayashi et al. (2000, 2001) irradiated several ice mixtures composed of methane, carbon monoxide and ammonia with high-energy protons. The results of quadrupole mass spectrometry and ion exchange chromatography showed the formation of amino acids, such as glycine and alanine, and some hydrocarbons. Garrod and Herbst conducted charged particle induced photodissociation calculations to model chemical changes from interstellar radiation field and galactic cosmic rays and reported the production of complex chemicals such as formic acid, methyl formate and dimethyl ether (Garrod and Herbst, 2006).

One common feature of these studies is that they all consider organic synthesis on the surface, which is true for high-energy photons such as UV, X-rays and low energy protons (~ keV – MeV). However for higher energy particles such as GCRs whose energies are ~ 10 GeV and beyond, the secondary particles penetrate below the surface. Particles such as electrons, positrons, neutrons and photons produced in interactions have very short ranges and are confined in a relatively small volume. Particles with the highest range are muons as shown in figure 2 and are the primary source of GCR-induced radiation in such environments. In order to validate this hypothesis, one can irradiate samples with muons produced in accelerator experiments. Muons can also be approximated with electrons in laboratory experiments to a certain extent because electrons also undergo electromagnetic interactions like muons, however they lose energy very quickly, which makes this test possible only at low energies. Based on the studies cited above, additional mechanism supporting subsurface life could be direct organic synthesis induced by GCR induced secondary particles, especially muons at greater depths. There is experimental evidence of the formation of amino acid precursors on exposure to high-energy particles (Kobayashi et al., 2000; Kobayashi et al., 2001). This mechanism could be especially important in case of comets, as cosmic ray induced ionization is believed to be the main driver of cometary organic chemistry (Cottin et al., 2000). Organic synthesis occurring at the polar regions of the Moon, Mercury and other silicate bodies has also been proposed (Crites et al., 2013). There are studies of GCR induced
synthesis of organic molecules in Titan's atmosphere (Capone et al., 1980; Capone et al., 1981), production of oxidants on Europa (Chyba and Hand, 2001) and the possibility of an aerial biosphere on Venus (Dartnell et al., 2015).

The production of O₂, H₂O₂ and other oxidants on Europa’s surface by charged particles accelerated in Jovian magnetic field has been estimated in an earlier study (Chyba and Hand, 2001). They proposed that through impact gardening, these biologically useful chemicals could be transported to Europa’s oceans. Ionization through ⁴⁰K decay was also considered. Since GCRs are much more energetic compared to particles considered this the above study, in addition to producing these chemicals on Europa’s surface, GCR secondaries can directly produce them in Ice below the surface. Let us now calculate the energy deposited in the ice shell of Europa from GCRs. The average energy deposited from 0 to 1 meter depth is ~ 10^{15} eV/g/yr. For this 1-m shell for entire Europa, the total energy is ~ 1.6 \times 10^{32} eV/yr, which would produce 2.4 \times 10^7 moles/yr of H₂ and O₂. This scenario is valid in other cases too where non-photosynthetic chemicals can be produced in subsurface environments using this mechanism.

3. Implications on the origin of life and possibility of finding life beyond Earth

It is believed that ~ 3.5 - 4 Gyr ago, when life originated on the Earth, the sun was in a highly active phase. In this scenario, the Earth's surface was likely to be bombarded by a high flux of energetic solar particles and super CMEs - Coronal Mass Ejections. Enhanced flux of solar particles and variability in the GCR flux can also enhance the rate of lightning (Erlykin and Wolfendale, 2010), and provide energy to the prebiotic soup to synthesize amino acids and other organic compounds forming the building blocks of life (Miller et al., 1976). If the solar particles are sufficiently energetic (>10 GeV) they can produce secondary particles capable of penetrating underground and in water (Khalchukov et al., 1995; Atri and Melott, 2011), providing a small source of energy away from direct exposure to high flux of harmful UV radiation on the surface. Solar particles typically reach energies of 100s of MeV during violent eruptions and in some cases greater than 10 GeV (Tylka and Dietrich, 2009). Typical SPEs (Solar Proton Events) produce a fluence of about 10^9 protons/cm² on earth. It is highly likely that such eruptions might have occurred on the Sun at a high rate
generating intermittently an increased flux of secondary particles at a high rate, underground and in the oceans. A combination of particle flux along with water and nutrients might provide ideal conditions for life to originate and evolve until conditions on the surface become optimal.

Since independent/freely-floating or “rogue” planets are not tied to any stellar system, they do not receive a steady stream of photons from a parent star. A mechanism has been proposed which could support life on such planets with a combination of sufficient pressure and radioactive heat (Stevenson, 1999). Alternatively, GCRs and radioactive materials can be a steady source of energy on such planets. The mechanisms proposed in this paper can be used to synthesize biologically useful chemicals and power such ecosystems. Europa is believed to have an abundance of liquid water below its thick ice shell (Chyba and Phillips, 2001). GCR-induced particles, although cannot provide energy in the ocean, as discussed earlier, they can provide ingredients and fuel to a potential ecosystem in its ice shell.

Measurements made by the Planetary Fourier Spectrometer onboard the Mars Express spacecraft found the average methane mixing ratio to be $10 \pm 5$ ppbv, with a variation between 0 and 30 ppbv depending on the location (Formisano et al., 2004). In situ measurements made over a period of 20 months with the Sample Analysis at Mars (SAM) instrument on board the Curiosity rover at Gale Crater have shown a background level of $0.69 \pm 0.25$ ppbv and occasional enhanced levels up to $7.2 \pm 2.1$ ppbv (Webster et al., 2015). The observed level of methane and its variations cannot yet be explained by standard physics and chemistry models (Atreya et al., 2007; Lefevre and Forget, 2009). The presence of indigenous nitrogen in sedimentary and aeolian deposits using the SAM instrument on-board the Curiosity rover was reported recently (Stern et al., 2015). Also, observations of hydrated salts – magnesium perchlorate, magnesium chlorate and sodium perchlorate on the Martian surface were recently announced (Ojha et al., 2015). Since typical redox reactions require only a few electron volts of energy, the possibility of methane and other gases such as $N_2$ and traces of $O_2$ being byproducts of an ionizing radiation-induced ecosystem cannot be ruled out. Methanogens can use radiation-induced hydrogen for abiogenic hydrocarbon synthesis. The presence of $CO_2$, hydrated salts and nitrogen, coupled with GCR-induced ionization could power such an ecosystem. As in case of
Candidatus Desulforudis audaxviator, the total energy produced by radioactive rocks is divided between radiolysis-powered metabolism, radiation damage and damage repair, we assume that a fraction of this energy deposited by GCRs will be utilized for metabolic purposes.

4. Conclusions

Studying the biological effects of ionizing radiation is a growing area of research. Much of the effort has been dedicated on examining its damaging effects on human health in context of radiation oncology, nuclear accidents and astronaut health in outer space. Several experiments have shown ionizing radiation to synthesize organic compounds on interaction with ice mixtures. The discovery of Candidatus Desulforudis audaxviator thriving 3 km below the Earth’s surface powered by radiolysis opens up new possibilities of biological interaction with ionizing radiation. GCRs produce secondary particles that deposit energy in the subsurface environment, and muons are able to penetrate even in deep subsurface environments. We have arrived at conceivable mechanisms through which the kinetic energy of GCR-induced particles can be used to produce biologically useful products such as organics and utilize energy for radiolysis to power a potential subsurface ecosystem. Ionizing radiation causes damage, and just as in case of D. audaxviator, a part of the energy deposited in subsurface environments can be used for repairing damage and the rest for chemical reactions and potentially biological use.

We conclude that Galactic Cosmic Rays are a steady source of ionizing radiation throughout the Galaxy and beyond. Their secondary component can deposit energy underground; muons especially can penetrate several kilometers underground (Atri and Melott, 2011; Atri and Melott, 2014; Dorman, 2004; Gaisser, 1990; Groom et al., 2001; Khalchukov et al., 1995; Mei and Hime, 2006). We demonstrate that GCR-induced radiolysis is a steady source of energy for subsurface environments and could be a viable source of energy supporting such an ecosystem. GCR-induced muons provide energy in deeper environment, however the energy falls rapidly with depth. Muons can directly interact with the medium with essential nutrients and synthesize basic chemicals vital for life to develop, analogous to the experiments with high-energy protons and ice mixtures (Cottin et al., 1999; Garrot and Herbst, 2006; Holtom
et al., 2005; Hudson and Moore, 1999; Kobayashi et al., 1995; Kobayashi et al., 2001).

The proposed mechanisms open up new possibilities of life in subsurface environments on Europa, Mars and other planetary bodies, especially ones with negligible atmospheres. Ionizing radiation-powered life can either thrive independently, or can consume a combination of sources such as heat from chemical and geological processes. GCR-induced radiolysis can produce hydrogen and can be used by methanogens for abiogenic hydrocarbon synthesis. The prospect of methane and other gases being byproducts of an ionizing radiation-induced ecosystem cannot be ruled out. There is a possibility of life on icy objects in the interplanetary medium such as comets, and other bodies in the interstellar environment. This energy source could support life locked inside icy objects and facilitate efficient transportation conferring to the panspermia hypothesis. Since rogue or independent planets also receive a steady flux of this radiation, there is a possibility of a thriving subsurface ecosystem on such planets. We suggest ground-based laboratory tests that can be conducted to validate both the hypotheses present here.

Acknowledgements

The author acknowledges Arnold Wolfendale, Andrew Karam, Adrian Melott, Jacob Haqq-Misra and Steven Hsu for their helpful comments on an earlier draft of the manuscript. This work made use of the Extreme Science and Engineering Discovery Environment, supported by the National Science Foundation grant number ACI-1053575.

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![Figure 1: Subsurface energy deposition rate in ice as a function of depth for a planet without an atmosphere.](image-url)
Figure 2: Subsurface energy deposition rate as a function of depth for Earth.
