On the possibility of cosmic ray-induced ionizing radiation-powered life in subsurface environments in the Universe

Dimitra Atri

Blue Marble Space Institute of Science
1200 Westlake Ave N Suite 1006
Seattle, WA 98109
dimitra@bmsis.org

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. An additional source of radiation in the subsurface environments is secondary particles, such as muons generated by Galactic Cosmic Rays (GCRs). It is a steady source of a small amount of energy, and the possibility of a slow metabolizing life flourishing on it cannot be ruled out. Muon-induced radiolysis can produce H₂ which is used by methanogens for abiotic hydrocarbon synthesis. We propose three mechanisms through which GCR-induced secondary particles, which are able to penetrate in deep subsurface environments, can be utilized for biological use. (1) GCRs injecting energy in the environment through muon-induced radiolysis, (2) organic synthesis from GCR secondaries interacting with the medium and (3) direct capture of radiation with the help of pigments such as
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 solar photons is the primary way by which the energy of the sun is transferred to living systems. The energy of a typical photon is about 2 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, 2000; 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 an 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 and astronaut health in outer space (Cucinotta and Durante, 2006; Durante and Cucinotta, 2008).

Nevertheless, high dosage of ionizing radiation can enable organisms to evolve mechanisms to survive in extreme conditions (Thornley, 1963). There have been several studies where radiation resistance has been developed in extreme radiation environments (Mattimore and Battista, 1996; Mironenko et al., 2000; Mosse et al., 2000). Other reports indicate constructive interactions with ionizing radiation, inducing growth and radiation resistance (Meredith and Sarna, 2006; Dadachova et al., 2007; Dadachova and Casadevall, 2008).

Melanins are complex polymers found in almost all biological kingdoms having a variety of properties including the ability to absorb radiation. It can
act both as a shield against radiation, as well as a transducer, converting the energy from radiation to metabolic purposes (Meredith and Sarna, 2006).

Geochemical processes are well known to support subsurface life (Ghiorse, 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 beta and gamma radiation. Secondary particles interact with the environment and provide energy for chemical change. Organisms can use these particles directly or indirectly for metabolic purposes. Candidatus Desulforudis audoxviator is such an example, which thrives in a radiolysis-powered ecosystem. It is able to extract carbon from dissolved CO$_2$ and nitrogen from the rock, and utilize them to synthesize amino acids. Such an organism can thrive in subsurface environments on Mars, Moon, Europa or other planetary systems in the presence of radioactive substances.

Here, we aim to take this one step further, and propose that 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). Muons are secondary products of cosmic ray interactions with the atmosphere and/or the surface of the planet (Gaisser, 1990). They can travel several kilometers depending on their energy (Dorman, 2004; Stanev, 2010), and as we demonstrate later, possibly produce ionization required to support minimal metabolism.

We will first review the relevant experimental work in this area and then propose mechanisms through which life can utilize this radiation in subsurface
environments. We will then discuss its implications on finding life on the Moon, Mars, Europa and elsewhere in the Universe.

2. Ionizing radiation and biology: A review of experimental work

Ionizing radiation interacts with ice, and in the presence of commonly available chemicals (in the Solar System), can synthesize amino acids and other organic compounds. It also interacts with melanin pigments present in some microbes. Some studies have concluded that melanin can behave both as a shield and as a transducer. In this section, we will focus on experimental results that center around the non-destructive biological effects of ionizing radiation.

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). 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, H₂CO and CH₃OH (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, C₆H₁₂N₄), 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. 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's experiments with protonated ions also showed the production of complex chemicals such as formic acid, methyl formate and dimethyl ether (Garrod and Herbst, 2006).

These experiments clearly demonstrate that a combination of ionizing radiation and nutrients can synthesize biologically useful chemicals in extraterrestrial environments. We shall now focus on other experiments where ionizing radiation can be utilized for additional purposes.

New experimental data on the role of melanin in energy capture had emerged as reported in Dadachova et al. (2007), and Dadachova and Casadevall (2008). Their observations indicated that melanized fungal species respond to ionizing radiation with enhanced growth. They also examined the possibility of melanins having energy harvesting functions similar to chlorophylls. 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. The south-facing slope of the canyon receives 2-8 times higher solar radiation than those on the north, and Aspergillus niger found there contains 300% higher levels of melanin than that found in the north facing slope (Singaravelan et al., 2008). In another set of experiments, Alternaria, Aspergillus, Humicola, Oidiodendron, and Staphylotrichum were exposed to up to 4000 Gy of $^{60}$Co and the ones growing in the south slope with higher melanin showed higher growth rates than the north slope ones (Volz et al., 1997). Several groups have studied these effects on melanized fungal species at Chernobyl accident site (Mironenko et al., 2000) and in nuclear reactor pool water (Mal'tsev et al., 1996).

Interestingly, many fungal species also have very high radiation resistance. Bacterium Deinococcus radiodurans is the focus of numerous studies and is the most radioresistant microbe with a 10% survival chance (LD10) at 15 kGy. Many fungi too have LD10 values exceeding 5 kGy. D. radiodurans have a
specialized recombination system for DNA repair from ionizing radiation. 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).

Radiotropism is a term used to describe the growth of fungi from exposure to radionuclides (Zhdanova et al., 2004). Most radionuclides emit beta (electrons and positrons) and gamma (photons) radiation and studies have shown that exposure to both sources promoted directional growth of fungi (Zhdanova et al., 2004). Exposure to $^{121}$Sn and $^{137}$Cs sources showed that the spore germination in species increased considerably, a phenomenon also known as ‘radiostimulation’ (Zhdanova et al., 2004).

Presence of several microorganisms has been studied in the Russian Mir Space Station as well as the International Space Station (Alekhova et al., 2005). The organisms consist of both bacteria and fungi, and are exposed to about 4 cGy of ionizing radiation per year. Many bacteria and fungi in these environments have been found to be pigmented or melanized (Baranov et al., 2006).

Dadachova et al. concluded that ionizing radiation changed the electron spin resonance (ESR) signal of melanin, making it more efficient in acting as an ionizing radiation transducer (Dadachova et al., 2007). Experiments have shown increased metabolic activity in melanized *C. neoformans* relative to non-melanized ones, indicating the enhancement of the electron transfer properties of melanin. The authors concluded that melanin played a major role in protecting the organism against ionizing radiation and these radioprotective properties arise due to its chemical composition, free radical quenching, and spherical spatial arrangement (Dadachova et al., 2008).

*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 producing secondary particles generates H\(_2\). Radiolytic H\(_2\) is used by methanogens for abiotic hydrocarbon synthesis. It provides them with the energy to sustain a minimal metabolism. Studies have shown that H\(_2\) produced through geochemical processes can be utilized for metabolism, independent of photosynthesis (Stevens and McKinley, 1995). This mechanism requires only water along with a source of radioactive decay particles.

3. Proposed Mechanisms

3.1. Galactic Cosmic Ray-induced radiolysis

For planets with substantial atmospheres, the primary GCR particles strike the atmosphere and produce a cascade of secondary particles. This cascade is 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). 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. They only undergo electromagnetic interactions and lose about 2-8 MeV energy per gram 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). Figure 1 shows the energy deposition rate of muons as a function of their kinetic energy. The energy deposition rate in water is slightly higher than in rock below 400 GeV, which represents a very large fraction of the muon energy distribution underground. For comparison, the mean energy of muons on the Earth's surface is about 4 GeV (Atri and Melott, 2011). Figure 2 shows the range of muons in rock and water as a function of their kinetic energy.
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). Mars' surface radiation dose is several orders of magnitude higher than that of the Earth due to a thin atmosphere. These energetic particles can also have non-destructive properties. As the particles traverse in a medium and lose kinetic energy, their destructive capability reduces as they produce low amounts of ionization. Figure 3 shows the total ionization produced by muons in rock and water as a function of their kinetic energy. As we show later, the ionizing energy is similar to energies observed in radioactive decay processes underground.

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). Figure 4 shows the energy deposition rate of muons calculated based on their underground flux and their ionization rate. The data for the underground muon flux is obtained from Mei and Hime (2006), and the energy deposition rate has been obtained from Groom et al. (2001). The energy deposition rate ranges from \(2 \times 10^5\) eV/g/m\(^2\)/s at a depth of about 1 km.w.e and goes down to 1 eV/g/m\(^2\)/s at a depth of 10 km.w.e. The radiolytic model calculations by Lin et al. yielded the net dosage range of alpha particles between \(4.25 \times 10^5\) - \(8.52 \times 10^5\) eV/g/s, beta particles between \(6.58 \times 10^4\) - \(4.27 \times 10^5\) eV/g/s, and for gamma rays between \(4.00 \times 10^4\) - \(2.25 \times 10^5\) eV/g/s (Lin et al., 2005). One can also infer from the plot that the muon energy deposition transitions from ionizing to non-ionizing at the depth of below 7 km.w.e. This is with reference to the ionization rate of a hydrogen atom (13.6 eV) and changes from material to material. Our atmosphere, for example, produces an ion pair at 35 eV. Even though these calculations are performed for the underground muon flux on the Earth, they can be done for other planetary bodies as well. Life can invent a variety of mechanisms to utilize such large range of energy injected underground. 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).

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 temperature ranges. 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 a biosphere thriving on this energy source based on other biochemical bases, and might necessitate alternate approaches to detect life 'as we don't know it' (Azua-Bustos and Vega-Martínez, 2013) in deep subsurface environments on Earth and elsewhere.

### 3.2 Organic synthesis

Additional mechanism supporting subsurface life could be direct organic synthesis induced by GCR induced muons. This 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) and the possibility of an aerial biosphere on Venus (Dartnell et al., 2015).

### 3.3 Direct capture of ionizing radiation

Chlorophyll is an excellent transducer that converts the energy of solar photons to energy useful in biology. On the other hand, as described earlier,
studies have shown that when ionizing radiation becomes the dominant source of energy, some organisms use other pigments to utilize their energy (Dadachova et al., 2007; Dadachova and Casadevall, 2008). Melanin is the key known substance that can utilize ionizing radiation directly for biological use (Zhdanova et al., 2004). It can act both as a shield from radiation (Mosse et al., 2000), as well as a transducer (Hill, 1992), converting energy for biological use. Melanin can change its electrical properties on exposure to radiation, and in this way develop mechanisms to harvest the energy. As we know, ionizing radiation can be destructive, especially at higher-energies; it can be useful when its energy becomes low, deeper in the ground. A possible mechanism could be a pigment that could utilize the energy of muons directly for biological use.

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

It is believed that ~ 3 Gyr ago, when life originated on the Earth, the sun was in a highly active phase. In this scenario, the Earth's surface is likely to be bombarded by a high flux of energetic solar particles or super CMEs - Coronal Mass Ejections (Airapetian et al., 2014). Elevated 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 muons capable of penetrating underground and in water (Khalchukov et al., 1995; Atri and Melott, 2011), providing a source of energy away from the 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). Such eruptions might have occurred at a high rate (Airapetian et al., 2014), producing a steady flux of muons underground and in the oceans. A combination of muon 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 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.

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 be explained by standard physics and chemistry models (Atreya et al., 2007; Lefevre and Forget, 2009). Similarly, excess $N_2$ on Pluto cannot be accounted for by standard means of production (Singer and Stern, 2015). Methanogens can use radiation-induced hydrogen for abiogenic hydrocarbon synthesis. The possibility of methane and other gases such as $N_2$ being byproducts of an ionizing radiation-induced biosphere cannot be ruled out. Europa is believed to have an abundance of liquid water below its thick ice shell (Chyba and Phillips, 2001). GCR-induced muons can provide fuel to a potential biosphere in its deep ocean.

5. Conclusions

Comprehending the biological effects of ionizing radiation is a growing area of research. Much of the effort has been dedicated on examining its harmful effects on human health. Lately, some studies have revealed that an exposure to radiation alters melanin's electrical properties and it is able to act as a source of harvesting radiation, just like chlorophyll. It opens up the possibility of the potential role of melanin in energy capture for biological use. Other 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, of which muons are able to penetrate in deep subsurface environments. We have arrived at conceivable mechanisms through which the kinetic energy of GCR-induced muons can be used by a potential subsurface biosphere. Following conclusions can be drawn:

1. There is growing evidence that ionizing radiation can be directly or indirectly exploited to develop radiation resistance and used as a fuel to power metabolism, as established from a number of experiments (Battista, 1997; Dadachova et al., 2007; Dadachova et al., 2008; Hill, 1992; Lin et al., 2005; Lin et al., 2006; Marrimore and Battista, 1996; Mironenko et al., 2000; Mosse et al., 2000; Singaravelan, 2008).

2. Galactic Cosmic Rays are a steady source of ionizing radiation throughout the Galaxy and beyond. Their secondary component, especially muons 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 muon-induced radiolysis is a steady source of energy for subsurface environments and could be a viable source of energy supporting such a biosphere.

3. 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).

4. Muons and its secondary products in the ionization track, such as electrons, positrons and gamma rays (Dorman, 2004; Gaisser, 1990) can possibly be directly captured by melanin-like pigments acting like
transducers and consume it as a source of energy (Dadachova et al., 2007; Dadachova et al., 2008).

5. The proposed mechanisms open up new possibilities of life in subsurface environments on the Moon, Europa and other planetary bodies. 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 biosphere cannot be ruled out.

6. 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.

7. Since rogue or independent planets also receive a steady flux of this radiation, there is a possibility of a thriving subsurface biosphere on such planets.

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References


Figure 1: Underground muon intensity as a function of slant depth. Based on the Depth-Intensity-Relation fit to the measured muon data obtained from 12 underground experiments around the world, compiled by Mei and Hime (2006).
Figure 2: Muon range in rock and water (column density) as a function of its kinetic energy (GeV), obtained from tables by Groom et al., 2001.
Figure 3: Total ionization produced by muons in rock and water. The vertical axis displays the total ionization in MeV/cm$^2$/g and the horizontal axis displays the kinetic energy of the muon in GeV. Data obtained from Groom et al., 2001.
Figure 4: Energy deposition rate (eV/g.m2.s) of muons as a function of depth (km.w.e.) in rock and water.