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Extreme life and robots on ice: Antarctica as an astrobiology analogue

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Abstract

Astrobiology is the study of life in the universe: its origins, evolution, distribution and future. By removing the distinction between life on our planet and life elsewhere in the universe astrobiology addresses deep, fundamental questions: How did life begin and evolve? Does life exist elsewhere in the universe? Where else might life have arisen and how can we find it? What is the future of life on our planet, and elsewhere? Astrobiology encompasses and embraces multiple disciplines, and is interdisciplinary in practice. The exploration of extraterrestial worlds begins at home. Antarctica is a powerful analogue for astrobiology. Extreme Antarctic environments can tell us about the potential habitability of other worlds, how life survives in extreme environments, and can help us test technology for robotic space missions. Europa, Jupiter's icy moon, is a prime target for astrobiology. Lake Vostok in East Antarctica is a powerful analogue for the liquid water oceans, and the possible life that may exist beneath Europa's icy shell. Studying extreme life in Antarctica reveals life as fascinating and resilient, diverse, unique. Antarctica can also be used as a field site for designing, testing and validating robotic technology to explore Europa, like the Europa Lander. Antarctica as an astrobiology analogue is inspiring, and embodies curiosity, discovery, exploration and possibility; placing life, and the value of our own planet, in a cosmic perspective. Astrobiology in Antarctica reflects the nature of science, puts Antarctica in context and proves to be an important lesson in the public understanding of science, science literacy and science communication.

Contents **Page**

Astrobiology

Astrobiology is the study of life in the universe: its origins, evolution, distribution and future (Des Marais et al. 2008). Its definition is as broad as its subject matter: life itself. Astrobiology embraces the search for life on other planets, while also being intimately linked with the study of life on our own. By removing the distinction between life on our planet and life elsewhere in the universe astrobiology addresses deep, fundamental questions: How did life begin and evolve? Does life exist elsewhere in the universe? Where else might life have arisen and how can we find it? What is the future of life on our planet, and elsewhere? Astrobiology encompasses and embraces multiple disciplines, and is interdisciplinary in practice (Des Marais et al. 2008). It crosses the fields of study of biology, physics, earth sciences, palaeontology, astronomy, space exploration technologies and philosophy (Chela-Flores 2011b).

Life on earth is the only example of life in the universe that we know of, so one of the distinct values of astrobiology lies in revealing the significance and bounds of life on our own planet. As a wide-ranging discipline it encourages us to strive towards a comprehensive and inclusive understanding of life (Des Marais et al. 2003). By dealing with the basic questions of life it is deeply bound to a cultural, as well as scientific context and significance. Astrobiology deals with the profound (questions of science and of culture): our place in the universe: who we are and where we come from. It also stands as an important lesson in the nature of science, science literacy and the public understanding of science (Oliver 2008). Astrobiology is inspiring, and embodies curiosity, discovery, exploration and possibility; placing life, and the value of our own planet, as the only place to harbour life, in a cosmic perspective.

Defining life

In order to understand the study of astrobiology, we must define its subject matter: life. This is no simple task. NASA defines life as the “self-sustaining chemical system capable of Darwinian evolution” (Benner 2010). In this sense ‘self-sustaining’ means the ability to reproduce or self-replicate. Darwinian evolution refers to the process that involves imperfect replication of genetic material (mutations in DNA on Earth), and these small, inherited variations are passed on to offspring, making them better suited for survival (natural selection resulting in increased fitness). The use of the word ‘system’ implies that an individual may be alive without embodying the definition of life (if they are past reproductive age, say). ‘Chemical’ system distinguishes that the organism is made up of chemical constituents, versus being a mechanical or electronic system which are not able to arise spontaneously (a watch cannot form on its own from a container filled with watch parts). While this definition of life is adequate, it does base itself on the assumption that possible life on other worlds will be like our own. Biochemistry (biological processes at the molecular level) is thought to be universal (Chela-Flores 2007; Pace 2001). Biological similarity is also important for instrumentation, since they are adapted to patterns of terrestrial life (Prieto-Ballesteros et al. 2011).

Habitability and extreme environments

How do we work out whether an environment is suitable for life? In astrobiology, this is termed ‘habitability’: the set of physical and chemical conditions that allow life to exist (Dartnell 2011; Preston and Dartnell 2014). So a habitable environment is one which can support life. Habitable extraterrestrial environments are possible candidates for the existence of life beyond our planet and are astrobiology targets. There are specific requirements for an environment to be habitable, as defined by the 'NASA Astrobiology Roadmap' (Des Marais et al. 2003; Des Marais et al. 2008).

Requirements for habitability:

(1) liquid water
(2) biologically essential elements
(3) energy source
(4) time

The limits of habitability are set by the bounds of environmental conditions that life can tolerate (Seckbach and Oren 2000). Physical or chemical conditions such as availability of liquid water, temperature, acidity or alkalinity, salinity, radiation and pressure must be within certain ranges for life to exist. Particular conditions will destroy biochemicals, like desiccation or radiation (Rothschild and Mancinelli 2001). The extremes of these ranges (very hot, dry or cold regions for example) can help define the bounds of habitability.

Extreme environments are stable environments that are characterised by physical and chemical conditions that are close to the limits which life can tolerate (Javaux 2006). Most extraterrestrial environments in our Solar System (and many beyond: the habitable environments of exoplanets are being further defined and classified, see (Seager 2013) can be classified as extreme. The study of extreme environments allows us to determine whether a particular environment may be able to support life. It is difficult to define 'extreme' environmental conditions since we do not know the baseline conditions for life, and the concept is human-derived (Dartnell 2011; Rothschild and Mancinelli 2001). Extreme can be considered scientifically in two ways, from an evolutionary standpoint, and one based on physical conditions (Rothschild and Mancinelli 2001). One viewpoint considers the earliest environment for life as 'normal', and any deviation from this as 'extreme'. This definition has limited value in the context of astrobiology, as we are not certain of the conditions under which life originated (and part of astrobiology is about understanding the origins of life). The second definition defines extreme as the maximum and minimum conditions that make it difficult for organisms to function. This is useful for astrobiology as it helps define the limits of habitability, and the potential for life to exist elsewhere in the universe.

Extremophiles

It is not only the physical and chemical conditions that determine habitability, it is the biological limits. The study of extreme life on Earth (extremophiles, able to survive extreme conditions) helps define these constraints. If life can thrive in hydrothermal vents under the ocean, or in rock kilometres beneath the Earth's surface, then life may exist elsewhere, and the bounds of habitability may be broader than we once thought (Preston and Dartnell 2014). Current estimates suggest that life can remain active at temperatures from -20°C to over 120°C, at a pH from approximately 0 to 13; in fresh water to highly saline conditions and pressures to at least 150MPa (Pappalardo et al. 2013). This astounding adaptability of extremophiles lends us a perceived diversity of potentially habitable environments within the Solar System and beyond. Extremophiles tell us about the limits of habitability, particularly the biological limits, and let us further define the range of conditions that are able to support life. There is also the question whether extremophiles must thrive in extreme conditions (optimal growth and reproduction rates), or can simply tolerate them (survive) (Rothschild and Mancinelli 2001). For astrobiology, extremophiles can be defined as organisms which are able to thrive under extreme conditions (Cavicchioli 2002).

Biological constraints on habitability: extreme life and life's origins
Extremophiles represent the diversity and adaptability of life, but they say nothing about the probability of life originating in the first place (Dartnell 2011). So, if other worlds are not able to provide the right conditions for life to arise, then the degree of habitability 'demonstrated' by extremophiles may be irrelevant (Dartnell 2011; Brack et al. 2010). There remains major challenges for describing the biological limits on habitability (Dartnell 2011). We need to look at the limits of habitability as informed by, yet distinct from the limits of extremophiles on earth (as these may be typical only of Earth and its habitats). We also need to examine pre-biotic chemistry that can deliver insights into the physical and chemical conditions that gave rise to the origin of life. It must be stressed that the fact that an environment is potentially habitable does not mean that it is inhabited (Prieto-Ballesteros et al. 2011).

Terrestrial analogues
The exploration of extraterrestial worlds begins at home. Without direct evidence or data for the environments or existence of life on other worlds, using analogues on Earth represents 'science in absentia' (Soare et al. 2001). Terrestrial analogues are environments on Earth that harbour conditions similar to those of other worlds (planets, moons, extraterrestrial bodies) other than Earth (Léveillé 2010). For astrobiology, they are used as field sites for space exploration activities, and are the best way to tell us about the possible habitability of extraterrestrial worlds, and to help plan and develop technologies for their exploration and search for life: past, present or potential (Léveillé 2009, 2010). Analogue sites are imperfect, as no site can be an exact replica of the planet or moon, and their level of similarity (of analogue to target) and fidelity (how confident we are in its similarity) is open to debate (Preston and Dartnell 2014; Lorenz et al. 2011). The value of terrestrial analogues lies in their being a testing ground for questions of habitability, extreme life and technology: of pursuing, understanding and evaluating the unexpected, not simply seeking out similarities (Lorenz et al. 2011). Through studying environments on Earth, we know that organisms can exist and thrive in a variety of conditions once thought uninhabitable (Preston and Dartnell 2014).

A 'three-tier' model has been applied to Earth's terrestrial analogue sites (Soare et al. 2001), and applied specifically to habitability (Preston and Dartnell 2014). A first order analogue is based on direct, empirical evidence (acquired by observation or experiment). Ice covered regions on Earth, for example, are first order analogues of the Polar ice caps of Mars. Indirect or highly suggestive or insubstantial evidence creates second order analogues. Studying terrestrial analogues is particularly important for this level because they have the potential to be proven false (Preston and Dartnell 2014). Fluvial landforms on Earth (created by rivers and streams) are second order analogues to similar landforms on Mars that may have been formed due to running water. Third order analogues are those for which there is no direct or indirect evidence, and are the realm of speculation and hypothesis. Since there is no evidence to suggest life exists elsewhere in the universe, other than Earth, organisms inhabiting extreme environments on earth are third order analogues. They are very important for telling us about potential habitability of other worlds, as they inform us about the limits of life on our own planet.

Antarctica as an extraterrestrial analogue

Antarctic analogues offer field testing ('*in-situ*') for astrobiology studies. The Antarctic continent provides examples of extreme environments on Earth. These environments can tell us about the potential habitability of other worlds and environments, how life survives in extreme environments, the potential for past life being preserved (as is speculated to have occurred on Mars (Fairén et al. 2010), and how to detect possible past or present signs of life (Preston and Dartnell 2014). All three tiers of terrestrial analogues are represented in Antarctica (Preston and Dartnell 2014). The Antarctic ice cap is a first order analogue for the polar ice caps of Mars. Lake Vostok, a subglacial lake four kilometres beneath the ice cap in East Antarctica is a second order analogue for the habitability potential of the putative ocean of Jupiter's moon Europa, for which there is much indirect evidence. Antarctic extremophiles can be considered analogues of the third order, as indicators of habitability and the possible present, past or future existence of life on other worlds, like Europa or Mars.

Antarctic analogues for Europa

Habitability: the case for Europa

Europa, the cold ice-bound moon of Jupiter (figure 1) is considered one of the most likely candidates for extraterrestrial life within our Solar System, so is a prime target for astrobiology studies (Prieto-Ballesteros et al. 2011). This is due to the presence of liquid water ocean (about 100 km deep) beneath its icy shell (about 15 km thick; Billings and Kattenhorn 2005). The presence of liquid water is the main requirement for habitability (Marion et al. 2003; Des Marais et al. 2008), so Europa fulfils this criterion. What about the other two necessities for habitability: biologically essential elements for life and an energy source? Data from the *Voyager* and *Galileo* have provided important insights into this (Chela-Flores 2011a). It is presumed that the ocean is salty, and that the ocean water contacts the moon's rocky mantle meaning chemical elements vital for life are likely present in the ocean. It is possible that the mantle is geologically active, potentially providing heat, a source of energy, to the ocean waters.

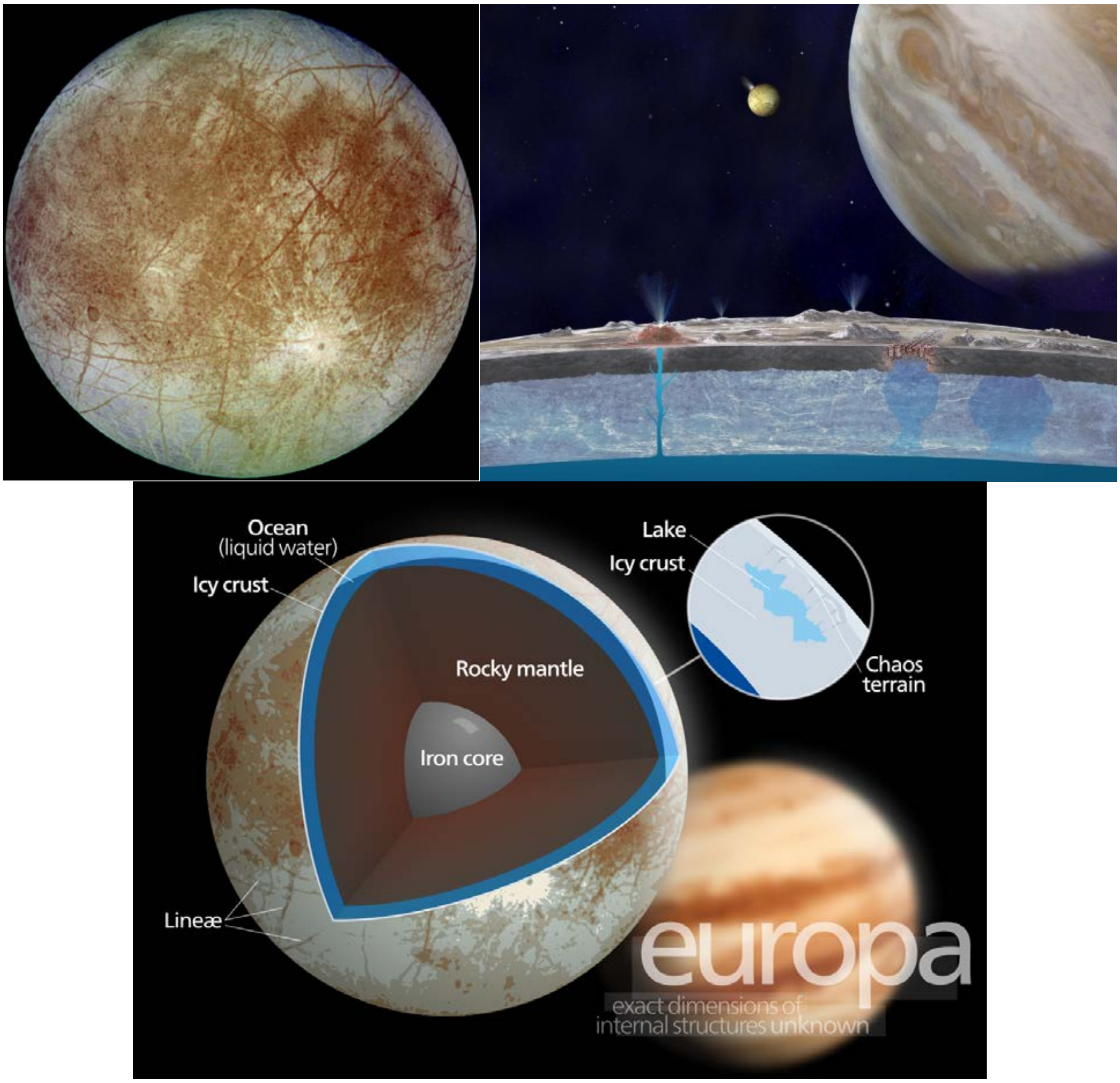

Figure 1: Europa, Jupiter's icy moon (top left) is a potentially habitable world with liquid oceans beneath its icy shell. Artists impression of a cross section of Europa, with an ice layer and an ocean beneath (top right and bottom) (NASA and Wikipedia)

Europa is a prime astrobiology target because life, if it exists, probably originated independently, deep within its oceans (as opposed to Mars, where life, if it exists, may be the result of possible interplanetary transfer) (Zelenyi et al. 2010). Europa does not seem to have suffered any geological cataclysms during its history, meaning the environment would not have changed dramatically, giving putative life the chance to adapt (Zelenyi et al. 2010). This is in contrast to Mars, which likely contained liquid water in the past, but there is no evidence of today, and has three distinct ages: past, middle, present. (Fairén et al. 2010). Europa is also of great interest to astrobiology because, due to its icy shell, and putative deep brine oceans, it is possible that potential life would have originated independently of the sun (Zelenyi et al. 2010) which would be of major scientific interest.

Lake Vostok: Antarctica's analogue for Europa's ocean
Buried almost 4 km beneath the Antarctic ice sheet, Lake Vostok (figure 2), may have isolated for 14 million years (Bulat et al. 2011). A subglacial lake at over 250 km long, 50 km wide and 1200 m deep, this extreme environment has been subject to complete darkness, high pressure (400 bars), low temperatures close to freezing, high levels of oxygen and low levels of dissolved organic carbon for millions of years (Siegert et al. 2001). Geothermal heating from the bottom of the Lake could create high temperatures (50°C), meaning microbes that thrive in heat may be present (thermophiles) (Bulat et al. 2011). It is a dynamic system, likely to be interconnected with other subglacial lakes, and the water within the Lake has a residence time of 80,000 years and the ice above the Lake may be 2 million years (Siegert et al. 2001).

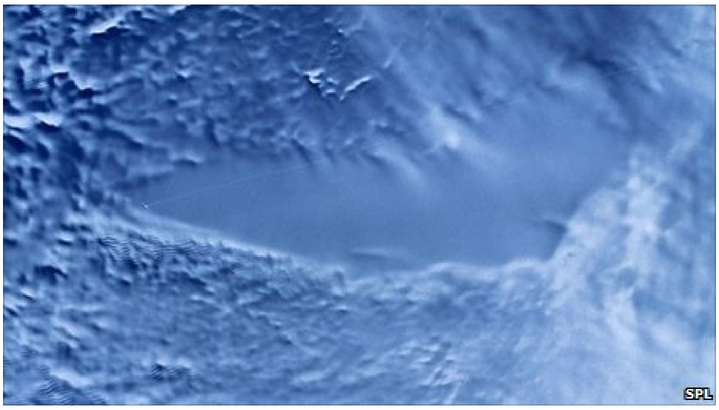

Figure 2: Lake Vostok, in East Antarctica is a subglacial lake that represents a powerful analogue to Europa's oceans. It can inform us about the potential habitability of Europa, and the possible life that may exist there (SPL).

Lake Vostok represents the most powerful terrestrial analogue for Europa's ocean and its potential habitability, as it provides a model for a number of different Europan environments (Lorenz et al. 2011). It provides an analogue for the ice-sheet-ocean interface, the ocean-floor environments, the hydrostatic pressure at the base of the ice, and for possible life in the ocean waters under the ice (Ellis-Evans 2001; Marion et al. 2003; Preston and Dartnell 2014). Almost 400 subglacial lakes have been discovered in Antarctica, and it is likely they are part of a large interconnected drainage system (Kennicutt and Siegert 2011). Other environments, such as ice-sealed Antarctic hypersaline lakes like Lake Vida are finding extremophiles at temperatures as low as -13°C (Murray et al. 2012). These offer more potential astrobiology models, showcasing the value of Antarctica as a powerful astrobiology analogue.

Extremophile life

Lake Vostok and implications for putative life on Europa
Lake Vostok provides an important analogue for the putative life forms that may exist within Europa's ocean. Due to the multiple stressors imposed on organisms from the environment (darkness, high pressure, low temperatures), any life would be classified as polyextremophiles. Polyextremophiles are extreme life that are capable of thriving under multiple extreme conditions simultaneously (Dartnell 2011). A Russian drilling program has recently been completed at Lake Vostok, having taken over 30 years, drilling to 3667 m of ice sheet, stopping just above the waters of the Lake, and obtaining a frozen sample of the Lake waters, and later, a fresh water sample.

Whether life exists in the Lake's waters is a challenge to determine. An early study (Priscu et al. 1999), from liquid water 3.5 km beneath the ice found a variety of polyextremophiles, and dissolved organic carbon levels that may support other organisms. Another study detected only thermophilic bacteria (Bulat et al. 2011). Fresh water samples have yet to be analysed, and it is highly possible that the organisms 'discovered' may have been a result of contamination. An interesting, important issues revealed by subglacial drilling in Antarctica have been the high risk of contamination, the importance of strict sterilisation procedures and the ethics of the quest for knowledge in the face of uncertainty. This emphasises the importance of Antarctic astrobiology analogues for informing our search for life elsewhere (Lorenz et al. 2011). Lake Vostok provides an important lesson in stringent sterilisation procedures, that should act as guidelines for informing the sampling of extraterrestrial ice, that may occur on Europa in the future (Bulat et al. 2011).

Robots on ice: testing technology in Antarctica for astrobiology missions

Antarctica provides an important analogue for the testing and validation of robotic space mission technology and instruments (Léveillé 2009). Planned and potential exploration missions to Europa are strongly motivated by its astrobiology potential (Prieto-Ballesteros et al. 2011). Any astrobiological mission requires the development of miniaturised instruments (like microsensors), capable of detecting biological activity or biologically relevant information, and that are able to perform autonomously on the surface of extraterrestrial worlds (Léveillé 2010). Such technology does not currently exist, and Antarctic analogues provide vital 'proof-of-concept' studies and 'field rehearsal' for such undertakings (Léveillé 2010; Lorenz et al. 2011; Zelenyi et al. 2010).

Europa Lander

Potential future missions, such as NASA's Europa Clipper and the Russian-led Laplace-Europa Lander mission have specific astrobiology goals: can the environment on Europa support life? Do traces of extinct life exist? Is there evidence of life on Europa? These questions cannot be answered simply with a flyby, remote sensing mission (Pappalardo et al. 2013). In order to search for life on Europa, we need to be able to detect it: we need to design robotic spacecraft capable of landing on the surface of the moon, and, ideally, drilling beneath its icy shell to reach the ocean waters underneath, and containing instruments and technology capable of searching for signs of life. This is where Antarctica proves to be a strong analogue for testing such concepts: the ice core obtained from almost 4 km deep into Lake Vostok could be used as an analogue for ice sampling of a Europa lander. Antarctic subglacial drilling technologies could also be used to develop and refine the technology needed for low temperature ice drilling, with proposed penetrators to drill through Europa's icy shell and possibly search for life (Gowen et al. 2011). The robotic craft also need to be able to detect life, or signs of present or past life, if it exists (termed 'biosignatures'). Antarctic analogue sites, like Lake Vostok and subglacial lakes, provide important development and validation of instruments for improving our ability to detect biosignatures, particularly at very low levels (Léveillé 2009; Prieto-Ballesteros et al. 2011; Lorenz et al. 2011).

Antarctic astrobiology: a lesson in science, communication and public outreach

Astrobiology in Antarctica reflects the nature of science

Studying astrobiology in Antarctica provides us with a tangible connection to the nature of science itself. The scientific search for life on other planets and bodies is a direct search for the *evidence* of life. This reveals an important aspect of science: that of evidence-based, critical thinking and encourages an 'evidence-based approach to everyday thinking' (Oliver 2008). Astrobiology can provide insight into the scientific method: observations, testing ideas, interpreting evidence, probability, prediction, and potential. Learning about astrobiology can help foster scientific literacy (Oliver and Fergusson 2007; Oliver 2008) and gives a greater appreciation of scientific thinking and science literacy is an essential everyday tool (Oliver 2008). As a relatively new discipline, astrobiology reflects the ever-evolving nature of scientific research, and, by spanning many fields of study, it mirrors the interdisciplinary nature of scientific enterprise (Fergusson et al. 2012).

There is evidence that science education is providing students with a false impression of the true nature of science and scientists: as concerned primarily with amassing facts and distanced from creativity (Fergusson et al. 2012; Oliver and Fergusson 2007; Oliver and Morrow 2003; Oliver 2008). By providing a context and a narrative for science, astrobiology in Antarctica helps to shed these negative stereotypes, and gives insight into the true nature of science. Its multi-disciplinary approach (inter-section of science, art, philosophy, technology, engineering, human discovery, rationalism) counters the fragmentary or increasing-specialisation approach that may be encountered in education (Brake et al. 2006; Taber 2010; Watkins et al. 2013). Astrobiology in Antarctica embraces creativity and bold ideas (does life exist elsewhere in the universe?), imagination (our place in the universe; using terrestrial models for extraterrestrial systems), exploration and discovery (beginning with exploration of our own world: finding the limits and bounds of life on Earth, from Earth's extreme environments). It makes scientific thinking and scientific literacy easier to understand because the narrative is readable here and it represents science writ large (Oliver 2008).

Antarctic astrobiology can be seen as a physical manifestation of the nature of science: its non-linear reality, the quest for knowledge, imbued with creativity, imagination, abstractions and distractions, unpredictability and curiosity (Oliver 2008). These are all traits that are very human, and an important part of our identity. Astrobiology in Antarctica is an inspiring motivator for public understanding of science, and as a strong model for public outreach (Oliver 2008; Taber 2010). Lake Vostok and other subglacial lakes provide a powerful analogue for extraterrestrial environments: even the ice-penetrating radar methods of discovering the Lake may prove a useful technique for Europa (Lorenz et al. 2011). Drilling into subglacial lakes is also an excellent metaphor for the narrative of science, the nature of human curiosity and the search for knowledge. The possibility of life within Lake Vostok tells us about the possibility of life on other worlds, like Europa. In turn, the search for life under the ice also reveals the heart of science: its narrative, humanness, the perpetual quest for knowledge and search for answers, and application and importance of scientific thinking.

Cosmic perspective

Astrobiology asks the deep questions: where do we come from, and, are we alone? Using Antarctica as an analogue gives us a more meaningful connection to our home (Earth) in space. By being a real visual reference for extraterrestrial worlds, even if imperfect (Lorenz et al. 2011), Antarctica offers people a tangible connection, a visual conduit to the often abstract, difficult to comprehend concepts of space (time, distance, vastness of scale) and the search for life elsewhere. It quite literally brings space down to earth. It tells us that the exploration of space begins with the exploration of our own world. Antarctica is a visual conduit for communicating about space exploration, as well as being a terrestrial analogue for extraterrestrial worlds. Visualising the extreme environments of Antarctica, and seeing the space mission robotic technology in the 'field' provides crucial context to space exploration (Léveillé 2010; Lorenz et al. 2011; Watkins et al. 2013). The fact that life can thrive in seemingly inhospitable conditions of Antarctica gives us a greater understanding and appreciation of the uniqueness of our own world. Antarctic astrobiology offers us a cosmic perspective of life, our planet, our species and our future, and ultimately, tells us of our own *value.* Earth holds the only example of life that we know of, so for this moment: 'here is where we make our stand' (figure 3).

Figure 3: 'That's here, that's home, that's us' – Sagan. Astrobiology in Antarctica offers us a similar cosmic perspective. As the only example of life that we know of 'Earth is where we make our stand' (Sagan). Earth, taken by the Voyager spacecraft from 6 billion kilometres away, occupies a fraction of a pixel in this image. (NASA)

Antarctica in context

Antarctica as an astrobiology analogue elicits an evocative imagining of Antarctica as a unique and extreme environment. Studying Antarctic extremophiles demonstrates the diversity, splendour and value of *life*, in its broadest sense. It shows microbes as fascinating, resilient life forms, challenging the assumptions about nature and bounds and limits of life (Billings 2006), in turn revealing *life* as fascinating and resilient, diverse, unique. Importantly, Antarctic astrobiology is a lesson in science communication, public understanding of science and public engagement with science (Oliver 2008; Taber 2010). Just like the cosmos, Antarctica can be rather abstract, but placed in this broader context of space, planetary science, exploration and discovery, it is given a visual reference and stimulus, and becomes engaging, tangible, exciting, and can become a 'powerful motivator' for understanding about Antarctica, and the origins and limits of life and environments, in a cosmic perspective (Lorenz et al. 2011). Astrobiology in Antarctica echoes and continues the continent's history of exploration and discovery, to push back the limits of knowledge. In our continuing pursuit to define the limits of life, and to venture to other worlds, Antarctica is a place where we can strive to reach new horizons, while discovering more about our own.

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