BioQuantum Record: Exploring otherness through extremophilic microorganisms

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ABSTRACT: The art-science collaboration BioQuantum Record aims to bridge scientific inquiry and artistic narrative using an astrobiological lens to explore fundamental questions regarding life, otherness, and the human perspective. We propose sending extremophilic archaea, "microbial astronauts", to potentially make contact with extra-terrestrial microorganisms. This transdisciplinary approach merges art and science by maintaining a liminal state of uncertainty and openness to new forms of knowledge. We further used anthropological tools to examine how meaning and knowledge are constructed across disciplines. This resulted in an art-science performance and exhibition, fusing scientific protocols with an artistic narrative to create a science fiction-inspired presentation. We conclude that astrobiology can be used as a means to explore otherness, with transdisciplinarity creating a shared space for encountering uncertainty and generating new inquiries.

Keywords: Science and technology, art and literature; Representations of science and technology; Popularization of science and technology

Introduction

“The chances of this happening might be one in infinity. Put it this way: the chance that there being intelligent alien life are, for me, infinitely higher than the chance there being a creator god." The answer from the comedian Tim Minchin when asked if he thought the universe was full of life [Minchin, 2009].

BioQuantum Record is the title of an evolving body of work emerging from an art-science collaboration rooted in astrobiology. It encompasses the development of exhibition and performance concepts, presentation of the project in talks, and meta-

level exploration of the nature of transdisciplinarity in relation to the concept of otherness. The core principle of transdisciplinary work is encounter: the scientist and artist meet in uncertainty. The artist engages with scientific material beyond aesthetics, the scientist approaches artistic inquiry beyond utility, allowing space for the unknown to act. Framed in a speculative sci-fi gesture, the BioQuantum Record project opens ontological and epistemological inquiries central to astrobiology, such as how we define and perceive life. This project revolves around the speculative narrative of a hypothetical edition of the Golden Record. Unlike the Golden Record sent aboard Voyager 1 and 2 to potentially contact extra-terrestrial intelligence [NASA, 2025], this transdisciplinary project proposes a biological connection based on molecular chirality. The “handedness” of molecules serves as both a poetic and scientific framework to explore how life might recognize and interact with something fundamentally “other”. While life on Earth almost exclusively uses left-handed (L-)amino acids and right-handed (D-)sugars as essential building blocks, extra-terrestrial organisms might use molecules with reversed chirality or a mixture of both elsewhere in the cosmos, forming a mirrored version of life, as we know it.

The narrative gesture proposes sending an artistic vessel prototype hosting biochemical materials and “a crew” of prokaryotes into space to initiate a chiral handshake with their extra-terrestrial siblings. The crew candidates are extremophiles from the archaeal domain, microorganisms that could potentially thrive in environments such as Mars or other planetary bodies. The conception of the vessel draws on the panspermia theory [Kawaguchi, 2019], the idea that life can travel between planets on space debris—echoing life’s potential as a cosmic traveler —resilient, adaptive, and capable of seeding worlds.

What happens when we send not just a message but life itself into the unknown? — In parallel with the scientific aspects of the project, this paper focuses on the artistic methodology emerging from art-science collaboration.

Post Voyager

The BioQuantum Record is a post-Voyager concept that critically engages with the implications of scientific progress and contemporary cultural-societal-philosophical thought, particularly the growing awareness of our pervasive anthropocentric worldview alongside an emerging recognition of the interconnected nature of life.

If we were to send another Golden Record into space today, what might the new record look like? Based on the premise that microbial collectives may be the first form of extra-terrestrial life we will come into contact with, how might we establish contact with them? Given the limitations of human sensory perception and scale, how can we meaningfully engage with microorganisms, whether terrestrial or extra-terrestrial? Despite technological advances, our understanding remains fundamentally constrained by the parameters of human experience.

Could we send microorganisms as intermediaries to make contact with their extra-terrestrial siblings? Although inevitably a gesture steeped in anthropocentric longing, the narrative framework playfully exposes the futility of transcending the limits of the human perspective. It becomes a narrative boomerang, which necessarily returns to us, asking Michael Ende's question: *"What is mirrored in a mirror that is mirrored in a mirror?"* [Ende 1984]. Here, the paradox transforms into a potential opening: a koan.

Microbial Astronauts

Our astronautical candidates are the extremophilic archaeal species *Metallosphaera sedula* and *Halobacterium salinarum*. *M. sedula* is a tough organism, growing optimally in hot, acidic, metal-rich environments [Huber et al., 1989]. It can be cultured on meteorite breccia and Mars regolith [Milojevic et al., 2021], even when adapting to heavy metals such as As, Cu, Zn, Cd, and Ni [Dopson et al., 2003], and is able to survive desiccation [Kölbl et al., 2020]. *H. salinarum* has evolved to live in high-salinity environments [Eichler, 2023], conditions that are not only found on Earth but are also widespread throughout the solar system. Enceladus and Europa appear to have salty oceans beneath their ice crusts [Lunine, 2017], and Mars allows for the formation of salt crystals [Pasteris et al., 2006; Davila et al., 2010], which can provide shelter for potential microorganisms by serving as shields against harmful radiation [Leuko et al., 2015].

Mirror Life and Chiral Handshake

Our proposal to enable contact between terrestrial and extra-terrestrial microbial astronauts is based on chirality. The term *chirality* comes from the ancient Greek word χείρ (*cheir*), meaning "hand," as it refers to the concept of "handedness." Chirality is a fundamental geometric property at the atomic level that is extremely significant in chemistry and has important implications in life sciences. Molecules with opposite chirality share the same atomic composition and connectivity but cannot be perfectly overlaid in space, similar to the left and right hand. In biomolecules such as amino acids and sugars, chirality arises from the presence of at least one carbon atom that engages in covalent bonds with four different substituents, giving rise to two possible forms, called enantiomers, which are chirally inverted "mirror images" in three dimensions (**Figure 1**).

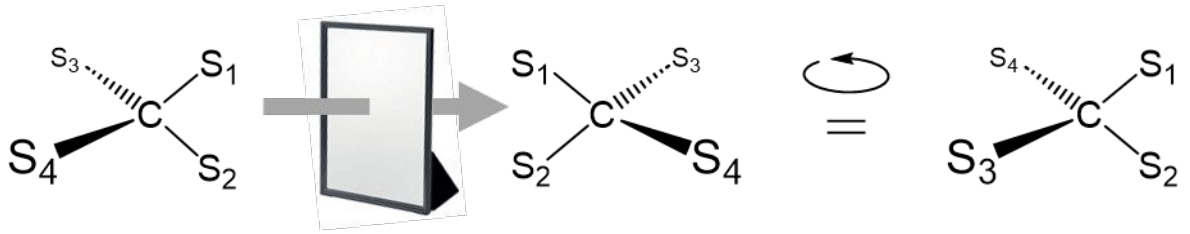

Figure 1: A tetrahedral carbon atom ("C") with four different substituents S_1, S_2, S_3, and S_4 (*e.g.*, different groups of atoms) can exist in two different "enantiomeric", chirally inverted forms.

Chiral molecules are optically active and can rotate the plane of polarized light in the opposite direction. One enantiomer rotates light to the left (counterclockwise),

whereas the other rotates light to the right (clockwise). Historically, the ability to rotate light in opposite directions has been used to distinguish between the two enantiomers. Although many more advanced methods not based on polarized light now exist, the historical terms are still in use in contemporary chemistry and biochemistry. The enantiomer that rotates light to the left is referred to as levorotatory (or "L-", from the Latin *laevus*, meaning left), whereas the one that rotates light to the right is referred to as dextrorotatory (or "D-", from *dexter*, meaning right).

Instead of using both enantiomers, life on Earth has evolved using almost exclusively L-amino acids and D-sugars [Barron, 2008]. This preference for one enantiomer over another in living organisms is referred to as "biological homochirality", a phenomenon that could serve as a potential signature for carbon-based life on other planets [Glavin et al., 2020]. Louis Pasteur wrote in 1874: "*The universe is asymmetric and I am persuaded that life, as it is known to us, is a direct result of the asymmetry of the universe or of its indirect consequences*". Inspired by this quote, and contrary to Louis Pasteur, we can imagine that if the reason why life is asymmetric depends on external bias factors, these can result in opposite outcomes if life were to emerge in other places in the universe [Ozturk and Sasselov, 2022]. Under these premises, we can imagine a carbon-based extra-terrestrial life that is a mirror version of life on Earth. Although enantiomers share the same chemical composition and atom connectivity, they can behave very differently in biological systems; one enantiomer may be curative, whereas the other may be ineffective or even harmful. The myth of Tantalus from Greek mythology springs to mind: Just as Tantalus was surrounded by food and water, which he could never reach, we might encounter molecules that appear similar but are fundamentally inaccessible or unhelpful to our life processes because of their chirality. On a planet where life is a mirror version of our life, we could eat and still die of hunger because our body simply could not utilize the molecules. The "handedness" of molecules is not only a scientific concept but also a poetic framework that allows us to explore one of the fundamental features of life. This invites us to consider what happens when life recognizes and interacts with something "fundamentally other": a possible mirror image of ourself.

Stepping back from the poetic lens, it is with the rigors of science that a final point deserves attention: While mirror-image biomolecules hold promising scientific and therapeutic potential, the scientific community has recently undertaken a collective effort to raise awareness of the risks associated with creating "mirror-image" life on Earth [Adamala et al., 2024].

A Chiral Gift – Testing Enzymatic Boundaries

Enzymes are proteins, *i.e.*, macromolecules composed of hundreds of homochiral amino acids linked together and then "folded" into a compact chiral three-dimensional structure capable of recognizing and binding to a "substrate" molecule and catalyzing its transformation into one or several "products" molecules. If the substrate is chiral, the (chiral) enzyme does not operate equally on both its native substrate and its

chirally inverted version, such as a left-hand glove that does not fit a right hand. An enzyme indeed selectively interacts with a particular spatial arrangement of atoms in its substrate, typically one enantiomer, while showing little or no activity toward its mirror image [Brik & Wong, 2003]. This selectivity arises from the three-dimensional complementarity between the active site of the enzyme and the specific configuration of its substrate. As such, even subtle changes (*e.g.*, chirality inversion) can completely abolish binding or catalysis. In biological systems, where molecular recognition and function critically depend on stereochemistry, a chirally inverted substrate is, in most cases, effectively invisible to the enzyme. In the framework of our art and science project, we focus on enzymes acting on “sugars”, also known as carbohydrates, which are biomolecules typically composed of multiple chiral carbon atoms, each linked to an oxygen atom. Among sugars, in addition to the pentoses (5 carbon atoms) D-2-deoxy-ribose and D-ribose, which are the core chiral parts of DNA and RNA, respectively, the hexose family (6 carbons, 6 oxygens) is the most abundant and includes D-glucose, a crucial source of energy in all Earth organisms, which use it as a starting substrate for metabolic pathways consisting of cascades of different enzymes. Although the enzymes and reactions they catalyze differ substantially depending on the type of organism, the starting substrate is always conserved: D-glucose.

One could expect that an extra-terrestrial form of life would also use glucose as an energy source. Five of the six carbons of glucose are chiral, and other hexoses in which the chirality of one or several carbons is inverted (so-called “diastereoisomers”) play important biological roles. For example, galactose is the carbon 4 (C4) diastereoisomer, mannose is the C1 diastereoisomer, and talose is the C1/C4 (**Figure 2**). One distinctive feature of glucose compared to other hexoses is its ability to adopt a “chair-like” three-dimensional shape (chemists call that a “conformation”), where the ring core–composed of five carbon and one oxygen atoms– positions its substituents predominantly in equatorial orientations (*i.e.*, lying in the plane defined by the chair). This arrangement makes glucose relatively flat and exceptionally stable, as the bulky oxygen atoms are quite far from each other, avoiding spatial conflicts (“steric clashes”). Such an “all-equatorial” configuration is thought to have been favored by evolution on Earth, making glucose the preferred fuel for life on Earth.

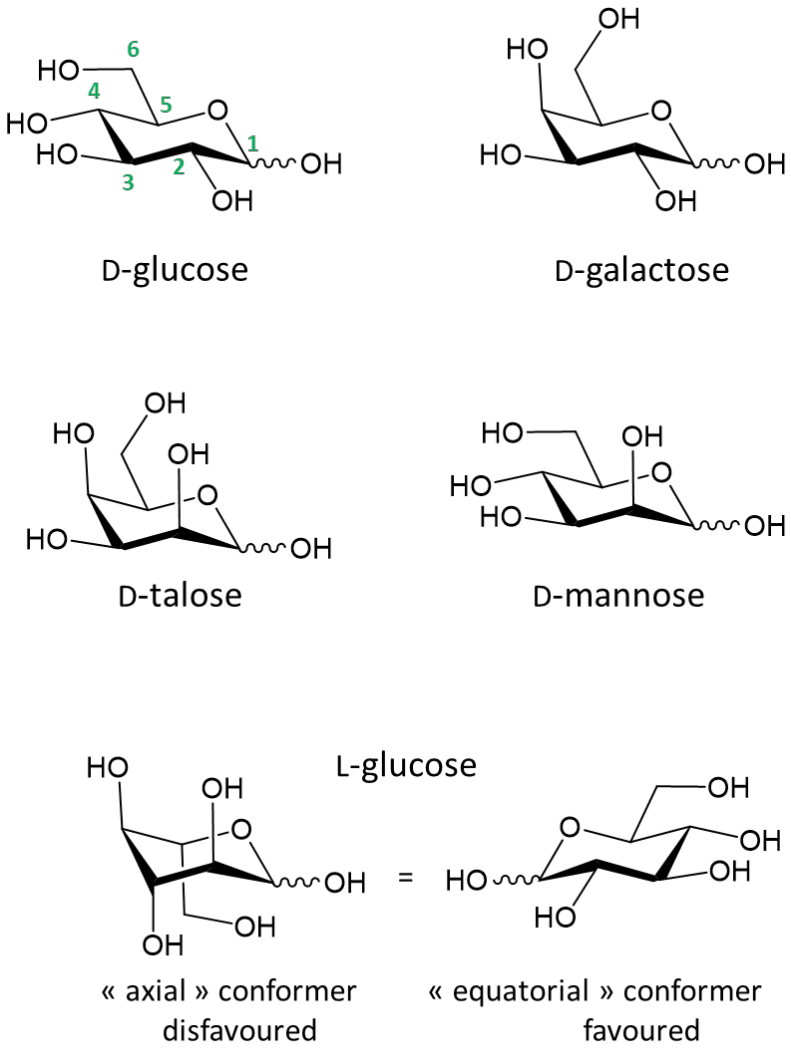

Figure 2: Schematic three-dimensional shapes (conformations) of selected hexoses. The compounds shown are D-glucose, D-galactose, D-talose, D-mannose, and the enantiomer L-glucose. Each six-atom ring ("pyranose") adopts a chair conformation, highlighting the differences in the orientation of hydroxyl groups (axial *vs.* equatorial) that distinguish the stereoisomers. In the case of L-galactose, L-mannose, or L-talose, only one or two substituents are axial, and the chair has the same orientation as L-glucose. In the case of D-glucose, the rotation of the bonds causes it to adopt an inverted chair conformation.

Thus, one could imagine that L-glucose, the enantiomer of glucose in which all five chiral carbons are inverted, could have been selected by homochirality-divergent earth-independent forms of life as a source of energy of choice because, as a mirror image, it shares all the stability features of D-glucose detailed earlier. L-glucose does not occur naturally in earth-borne living organisms but can be synthesized in the laboratory. It adopts an "inverted chair" three-dimensional structure, which is a mirror image of D-glucose (see **Figure 2**).

In its isolated form, glucose carbon #1 (C1) displays a hydroxyl (-OH) group (in addition to those at C2, C3, C4, and C6) that can rapidly interconvert between two chiral configurations, namely α and β (**Figure 3**); however, the C1 hydroxyl group can also form a covalent bond with another molecule, giving rise to "glycosides" (the

hydrogen atom, H, is replaced by another, typically a carbon). As a glycoside, the C1 carbon of glucose is locked in a fixed configuration, either α or β.

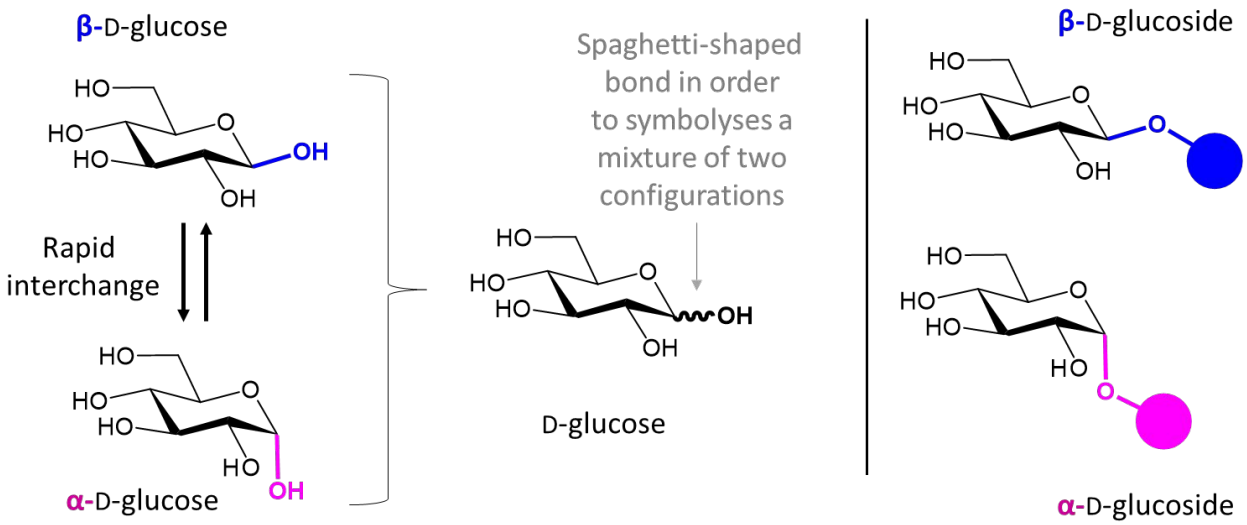

Figure 3: Isolated form of D-glucose, where the interconversion between its α and βC1 configurations is allowed, versus glycoside form of D-glucose, where C1 chiral configurations are locked.

Many organisms store glucose in polymeric forms, such as glycogen in animals and starch in plants, which can be depolymerized by enzymes on demand to release "free" isolated glucose, which is then used as an energy source. Besides its role in energy storage, cellulose–a glucose polymer composed of linear chains of several hundred to many thousands of β-D-glucose units (**Figure 4**)–is a crucial structural component of plant cell walls, which gives plants strength and rigidity, and is the most abundant organic polymer on Earth: terrestrial plants globally produce ~ 100 billion tonnes of cellulose every year.

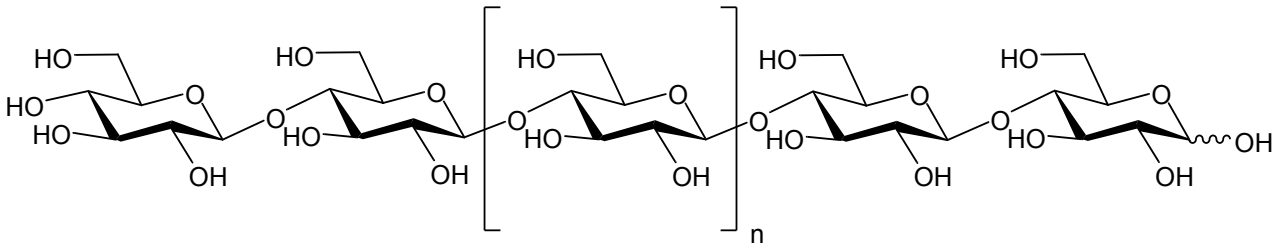

Figure 4: Molecular structure of cellulose.

We concentrated our work on β-glucosidases, enzymes that catalyze the breakage of the β-glucosidic bond through the addition of a water molecule (hydrolysis). If mammals do not produce β-glucosidase enzymes to digest cellulose on their own, they do have certain β-glucosidases for breaking down specific glucosides. However, many microorganisms, including archaea, bacteria (particularly ruminant gut microbiomes), fungi, and yeasts, express and secrete these enzymes. In our experiment, we sought to investigate whether the enzymes of our chosen microorganism could hydrolyze the β-glucosidic bond in a D-glucoside "molecular probe" compared to an L-glucoside probe. We do not expect Earth-borne enzymes to

hydrolyze the mirror-image substrate[1], and we aim to obtain visual feedback on its selectivity. In principle, the mirror-image substrate could only be efficiently hydrolyzed by an "alien" mirror-image glycosidase, thereby serving as precursors of our intended sweet "chiral gift", L-glucose. Our synthetic sugar probes are chromogenic substrates (*p*-nitrophenyl glucosides) that release a bright yellow compound (*p*-nitrophenolate) upon hydrolysis (**Figure 5**). The resulting color change provides a straightforward visual signal and can be easily measured, which is why these probes are commonly used in laboratory assays to monitor enzyme activity. *p*NPG is commercially available and has been extensively used as a probe to quantify the catalytic efficiency of a purified β-glucosidase enzyme [Riou et al., 1998; Lin et al., 2010] or to detect β-glucosidase secretion by microorganisms such as fungi [Madhu et al., 2009], bacteria [Strahsburger et al., 2017], and yeasts [Liu et al., 2020]. To our knowledge, no attempts have been made to monitor β-glucosidase secretion from archaea, although the presence of β-glucosidase has been evidenced [Schröder et al., 2014].

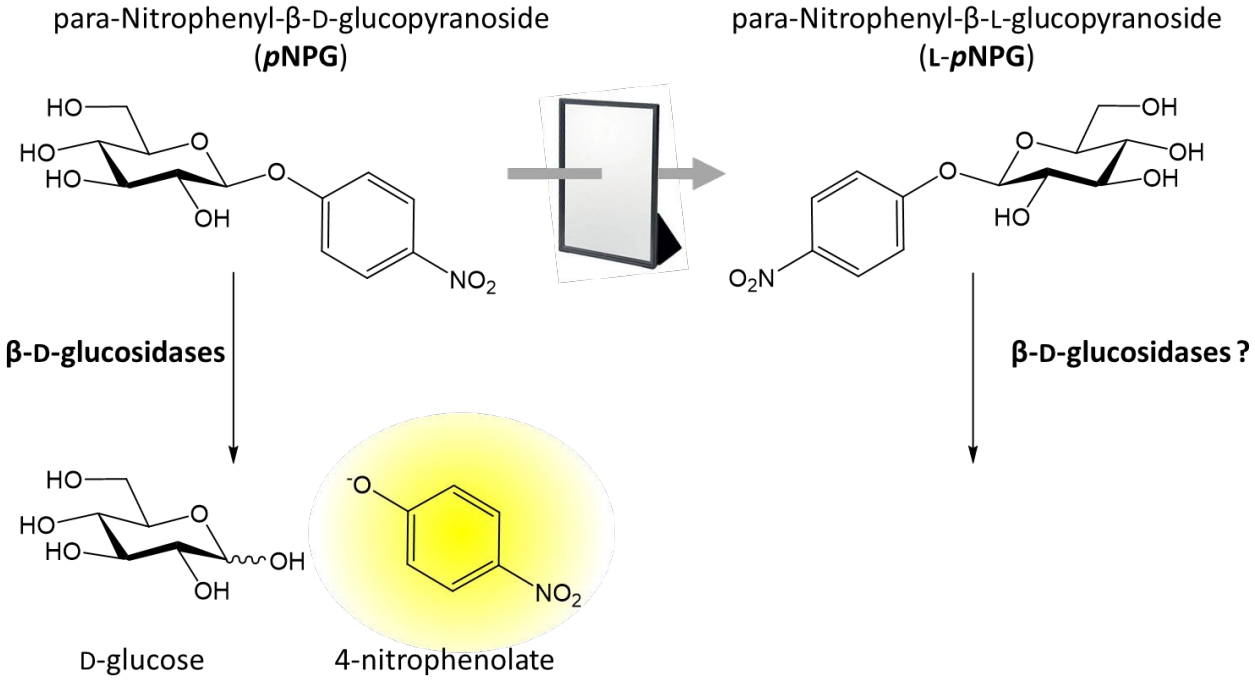

Figure 5: Enzymatic hydrolysis of para-nitrophenyl-β-D-glucopyranose (*p*NPG) releases bright yellow para-nitrophenolate, whereas the enzyme activity is expected to be null with respect to the L-*p*NPG substrate, which is the mirror-image version of *p*NPG.

Art, Space, and Astrobiology

Art finding inspiration in science and the intersection of art and science, especially microbiology, was introduced by Alexander Fleming the father of penicillin, who created drawings using different strains of bacteria [Dunn, 2010]. Subsequently, the use of microorganisms in art has gained increasing recognition, both as a distinct

[1] A few microbial enzymes with L-glucosidase activity have been reported. For example, studies have described L-fucosidases and L-rhamnosidases with a very weak ability to act on L-glucose linkages, to be seen as a "promiscuous" catalytic activity, not selected by evolution.

artistic medium [Hauser, 2020], and as a pedagogical tool for public science communication [Yarzábal Rodríguez & Batista-García, 2025]. A prominent example of biological art (BioArt) using microorganisms is Anna Dumitriu who fuses fine art, performance and BioArt techniques in art and science collaborations [Fawcett & Dumitriu, 2018; Dumitriu, 2024] including investigations of human-microbiome relations [Greenhough et al., 2020]. In parallel, Space Art engages with the space environment. An example is *Inner Telescope* by Eduardo Kac, created with astronaut Thomas Pesquet aboard the International Space Station [Kac, 2017]. Despite these precedents, art explicitly addressing astrobiology remains rare. Suzanne Anker's installation "Astroculture (Shelf Life)" [Anker, 2009-on going] is a notable exception, cultivating plants under spectral lights and connecting this work to NASA research on life-support systems.

Unlike previous projects that focus on plants or human perception in space, the BioQuantum Record project uniquely engages with extremophilic archaea as active participants, conceptualized as microbial astronauts, inviting a narrative that opens the imagination to the possibilities of life beyond Earth while merging artistic exploration and scientific investigation. To our knowledge, no other project has utilized extremophilic archaea in a space-art context, making this approach pioneering.

Materials and Methods

Microbial Cultivation

Metallosphaera sedula DSM 5348 was grown aerobically in DSMZ 88 medium with pyrite, as previously described by Gfellner et al. (2025a) in 1 L glassblower modified Schott-bottle bioreactors (Duran DWK Life Sciences GmbH, Wertheim/ Main, Germany). The stock culture was stored at −80°C in a solution containing equal parts of 50% glycerol and DSMZ 88 medium (50, 50, v:v). The DSMZ 88 medium contains 9.84 mM $(NH_4)_2SO_4$, 2.06 mM KH_2PO_4, 1.01 mM $MgSO_4 \times 7H_2O$, 0.48 mM $CaCl_2 \times 2H_2O$, and 0.07 mM $FeCl_3 \times 6H_2O$, and it also served as the medium for cell resuspension. Additionally, Allen trace element solution was added, which contains 0.91 mM $MnCl_2 \times 4H_2O$, 1.18 mM $Na_2B_4O_7 \times 10H_2O$, 0.08 mM $ZnSO_4 \times 7H_2O$, 0.03 mM $CuCl_2 \times 2H_2O$, 0.01 mM $Na_2MoO_4 \times 2H_2O$, 0.02 mM $VOSO_4 \times 2H_2O$, and 3.56 µM $CoSO_4 \times 7H_2O$. As previously described by Kölbl et al. (2017), 0.1% tryptone was added to the DSMZ 88 medium [19]. The pH was set to 2.0 using 5 M H_2SO_4. Pyrite was manually crushed with a hand grinder to achieve particle sizes between 63–100 µm, regulated by 63 µm and 100 µm mesh sieves, and then baked overnight at 180°C. Pyrite at a concentration of 10 g/L was added to 800 mL of culture. A 1 L bioreactor was assembled (**Figure 6**), maintained at a constant temperature of 73°C, and continuously stirred. A CO_2 flow at a total rate of 0.9 L/min (normalized to 1 atm and 0°C) was maintained for the interconnected triplicate bioreactor setup, resulting in a flow rate of 0.3 L/min for each bioreactor.

Figure 6: Artist Anna Steward and scientist Sebastian Gfellner together in front of a bioreactor of *M. sedula* culture grown on mineral pyrite in the laboratory of the host institution.

To track the growth of microbes, samples from the cultures were taken continuously throughout the growth phase, and cell counts were conducted using a microscope (Olympus BX51 with a Pixelink M20C-CYL camera) and a Neubauer Chamber (Carl Roth GmbH & Co. KG, Karlsruhe, Germany). Once the cultures reached the stationary phase, they were collected by centrifuging in sterile 50 mL Falcon tubes at 3220 × g for 40 minutes.

Furthermore, a 10 × concentrated *M. sedula* culture grown on pyrite was recultivated in 50 mL Erlenmeyer flasks with the following mineral materials: the two Mars analog materials JEZ-1 Jezero Delta Simulant (Exolith) and ESA01-E Martian basalt analog, pyrite, rutile, anatase, illmenite, and titanium dioxide, in a shake incubator set at 100 rpm and 75°C, over a period of 72 h. The harvested material was subsequently transferred in 300 µL steps (3 mL in total) to metal exposure wells and air-dried.

Halobacterium salinarum DSM 3754 was cultivated aerobically in DSMZ 97 medium[2] was used without additional $MnSO_4 \times H_2O$ in 50 mL Erlenmeyer flasks in a shake incubator set at 100 rpm and 37°C over a period of 504 h. The cultures were continuously and directly transferred into 1.5 mL Eppendorf tubes for further experiments. Additionally, part of the harvested material was subsequently transferred in 300 µL steps (3 mL in total) to metal exposure wells and air-dried.

Scanning Electron Microscopy

H. salinarum cells were cultivated as described above until they reached a high cell density, which was assessed by light microscopy. A 1 mL aliquot of the culture was fixed by adding glutaraldehyde (Sigma-Aldrich) to a final concentration of 2 %. The samples were fixed for 2.5 h at room temperature.

[2] https://www.dsmz.de/microorganisms/medium/pdf/DSMZ_Medium97.pdf

Following fixation, 100 µL of the cell suspension was applied to a Whatman® Nuclepore polycarbonate filter disc (0.2 µm pore size, 13 mm diameter; Cytiva). The filters were washed once with double-distilled water and air-dried at room temperature. The dried filters were mounted onto SEM Specimen stubs (12.5 mm diameter, 3.2 × 8 mm pin; Agar Scientific) using double-adhesive tape.

The samples were then sputter-coated with gold/palladium (Au/Pd) for 10 s at ~20 mA and 2.45 kV using a Polaron SEM Coating Unit E5100. Scanning electron microscopy (SEM) was performed using a ZEISS GeminiSEM with an in-lens detector operating at an electron high tension (EHT) of 5 kV.

Glucosidase Experiment

para-Nitrophenyl-β-D-glucopyranoside (*p*NPG, CAS RN: 2492-87-7) was purchased from TCI Europe N.V. Its mirror image, para-nitrophenyl-β-L-glucopyranoside (L-*p*NPG) has never been described, and was prepared following a three-steps synthetic route described for *p*NPG [Riou et al., 1998], starting from L-glucose (Sigma-Aldrich). Its ^{1}H NMR spectrum was consistent with the literature data for *p*NPG [Riou et al., 1998], and was identical to that of commercial *p*NPG, as expected for enantiomeric compounds. Similarly, reverse-phase HPLC analysis showed an identical retention time for *p*NPG. L-*p*NPG: **^{1}H NMR** (600 MHz, methanol-d$_4$) δ 8.20 (d, *J* = 9.3 Hz, 2H), 7.23 (d, *J* = 9.3 Hz, 2H), 5.14 (d, *J* = 7.3 Hz, 1H), 3.92 (dd, *J* = 12.4, 2.2 Hz, 1H), 3.74 (dd, *J* = 12.4, 5.7 Hz, 1H), 3.64 – 3.54 (m, 2H), 3.47 (dd, *J* = 9.3, 9.3 Hz, 1H). **MS** (ESI+): $[M+Na]^+$ *m*/*z* calculated for $C_{12}H_{15}NNaO_8$: 324.1, found: 324.0. **RP-HPLC** (C18 HR chromolith, 100 × 4.6 mm, 3 mL flow rate, solvent A = H_2O/TFA 99.9:0.1, solvent B = MeCN/TFA 99.9:0.1, gradient: 5 to 95 B in 5 min), t_R = 1.24 min.

β-Glucosidase was extracted from sweet almond seeds. Briefly, almond seeds (10 g) were ground in 100 mL phosphate-buffered saline (PBS) using a kitchen hand blender. The resulting suspension was filtered through a sintered glass funnel using a sand pad to prevent clogging, centrifuged at 20,000 RPG for 30 min, and finally filtered through a 0.2 µM membrane to obtain a clear solution, which was stored at 4 °C.

β-Glucosidase Chromogenic Assays

All experiments were performed in triplicates.

Control experiments using sweet almond β-glucosidase. Almond seed extract (30 µL) was diluted in PBS (270 µL), and 100 µL of a 20 mM aqueous solution of *p*NPG or L-*p*NPG, or water (negative control) was added (final probe concentration: 5 mM). The resulting solution was then incubated at room temperature. The release of para-nitrophenolate was monitored by the naked eye.

β-L/D-glucosidase assays on Halobacterium salinarum. To 300 µL of *H. salinarum* culture in DSMZ 97 medium, 100 µL of a 20 mM aqueous solution of either pNPG or L-pNPG or water (final probe concentration: 5 mM) was added, and the resulting suspension was incubated at room temperature. The monitoring of *para*-nitrophenolate release was monitored by naked eyes.

Results and Discussion

Point Zero: Entering the Lab

The artist arrives at the laboratory with ideas, sketches, and questions. Yet, despite all prior preparations, stepping into the lab means undergoing Ritual Zero: a deliberate un-knowing. Ritual Zero creates a space of open-ended inquiry, where the goal is not to narrow a field but to expand a perspective—to speculate and discover connections.. This methodological divergence can create productive friction between the artist and the scientific partner, whose training is to define variables, control conditions, and zoom in on specific, testable truths. The artist's expansive "what if" meets the scientist's precise "how".

The artist begins as an intruder in the lab. Someone who does not know the language does not belong and needs special attention, which eats into the precious time of the researchers. The routine laboratory procedures are disrupted. This causes irritation. However, this irritation is not a flaw; rather, it is the very mechanism of the practice. The artist, inhabiting the role of otherness, operates as a deliberate agent of uncertainty. This position of liminality is an active, extended field that provokes routine, evokes latent possibilities, and activates a fundamental shift in perspective, inviting collaborators to step into a space where their certainties are displaced.

Arnold van Gennep first introduced the concept of liminality in 1909 in his study of rites of passage [Van Gennep et al., 2019]. The term "liminal" comes from the Latin word *limen*, meaning a threshold or boundary. Van Gennep described liminality as the middle phase in a three-part process: separation, liminality, and incorporation. In the context of rituals, the liminal phase is the stage in which individuals have left behind their previous status but have not yet assumed a new one, entering a state of ambiguity, suspension, and openness. Victor Turner later expanded van Gennep's idea, emphasizing liminality as a period of profound potential, where structure and anti-structure coexist [Turner & Abrahams, 2017]. These "betwixt and between" states harbor the possibility of transformation.

In the BioQuantum Record project, the liminal state is not only a phase but also a method: a deliberate opening toward not knowing, allowing encounters and the emergence of new forms of knowing.

Immersion and Liminal Persona

We propose immersion to deliberately sustain the liminal state. By engaging hands-on with experiments, materials, and scientific practices, without seeking immediate mastery or closure, the artist remains open to the unknown. Immersion begins with attuning to the space by observing how people move, how structures are organized, and how scientific knowledge is practiced.

Crucially, this includes collaborating with scientists, not only to understand their theoretical frameworks, but also to participate in the tactile and material dimensions of their work. Interacting with protocols, tools and substances become a way of thinking through doing, where insight arises from direct encounters rather than detached observations. Sensory involvement—touch, texture, and proximity—can act as a portal for a different kind of knowing. This mirrors the resonance described by anthropologist Lisa Messeri in her ethnography of planetary scientists: a felt connection that transforms abstract concepts into something tangible through embodied, affective interactions with materials and processes [Messeri, 2016].

Through such immersion, a new persona begins to emerge: the lab shapes the artist's liminal identity. This liminal persona is twofold: it is both a state for engaging through the quality of encounter, and a role that, within the lab, echoes the function held by sacred tricksters in traditional societies, where disruption opens space for new ways of thinking [Plant, 2010]. It is within this space that artistic insight germinates.

When Science meets Art

The core principle of transdisciplinarity is humility: the willingness to recognize one's ignorance against the backdrop of the other and, by listening to the other, to perceive afresh with both the senses and the mind. Everything starts with finding and establishing a common language; a certain word linked to a specific task may not have the same meaning in art and science. The scientist, though guided by rational boundaries, is invited to open their imagination within the collaboration.

Artists and scientists have different ways of conducting their work. Artists often focus on the process of artistic creation, which involves constant reshaping and building on new ideas. They own the right to define when the work is completed. In contrast, scientists typically have no access to experiments once they are initiated. Any changes during the experiment tend to introduce errors. Therefore, it is crucial to carefully plan an experiment beforehand, accounting for potential errors, because once it has started, scientists can no longer intervene. Additionally, once an experiment is formalized in a scientific publication, the peer review process leads to a never-ending "specimen" that could also be proven wrong by future observations. The way of science is built upon continuous improvement and discovery, the imperfections that must be explained by others while opening new gaps of knowledge: a never-ending story.

Where science is rooted in empirical soil, artistic narratives can grow from it into speculative air. The artist has the freedom to imaginatively reinterpret or even bend physical laws within a narrative framework, something a scientist, by the nature of their discipline, cannot and would not aim to do. This divergence is a complement: where science seeks to explain, art speculates, evokes, or reframes. Working within the context of artistic imagination can enrich scientists' vision, potentially opening new research questions that enhance scientific curiosity.

Art can serve as a vessel for the parts of a scientist's psyche that resist rational frameworks—those impulses drawn to the beauty of the unknown or the enigma of existence. It offers a medium through which scientists can momentarily detach from logical paradigms and access deeper layers of imagination and consciousness.

Art and Science: Towards a Synthesis

From Art to Experiment: Stimulating the Scientific Process. A scientific question arose from an artistic narrative: Can our microbial astronauts carry the proposed sweet chiral gifts to their extra-terrestrial counterparts? Or will they "eat" it during their long interstellar travel, which would be quite inappropriate, impolite, and not diplomatically correct.

To ensure such interstellar political correctness, we tested whether our microbial astronauts, *M. sedula* and *H. salinarum*, could utilize L-sugars. We chose to design and focus on experiments with *H. salinarum* (**Figure 7**) because of its potential for glycolysis [Baati et al., 2024] and in contrast to *M. sedula*, of the cultivation modalities and the clarity of the cell-medium mixture to clearly observe a potential color activation in the previously described enzymatic hydrolysis of para-nitrophenyl-β-D-glucopyranose (pNPG), resulting in a bright yellow color.

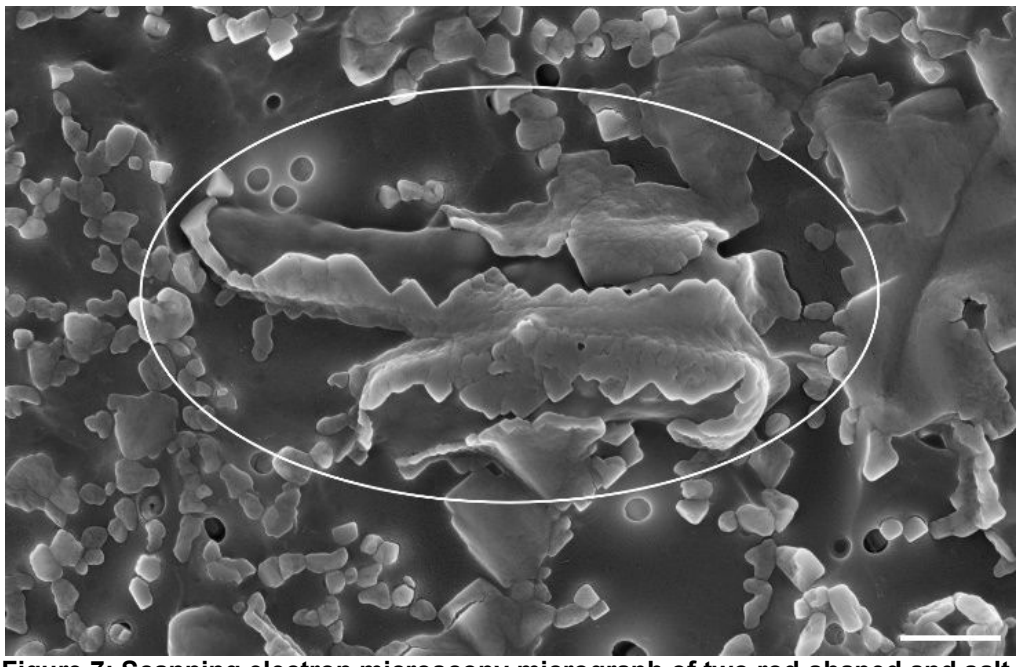

Figure 7: Scanning electron microscopy micrograph of two rod-shaped and salt-encrusted *H. salinarum* cells (white circle). The scale bar of 90 nm is illustrated in white on the bottom-right. The analysis was conducted at the Archaea Centre at the University of Regensburg (ZEISS GeminiSEM).

Glucosidase Experiment

Control experiment with sweet almond β-glucosidase. As a control experiment, we tested the activity of sweet almond β-glucosidase on both pNPG and L-pNPG probes. Incubation with pNPG rapidly produced a yellow color, reflecting the release of p-nitrophenolate upon enzymatic hydrolysis. The color intensity reached a plateau within 5 min, indicating complete substrate consumption. In contrast, no color change was observed with L-pNPG, even after extended incubation for up to 15 days, indicating the absence of any β-L-glucosidase activity.

Cell experiment. The microorganisms were first validated for viability before starting the experiment. During the incubation assays, no color change was observed in either *p*NPG- or L-pNPG-treated samples, even after 15 days, suggesting the absence of secreted β-glucosidase activity in *H. salinarum*.

Since it was also possible that other enzymes, such as nitroreductases [Akiva et al., 2017], could inactivate the chromogenic properties of *p*NPG and L-*p*NPG substrates, we added almond β-glucosidase to both samples after the 15-day period. This treatment led to a rapid color change to bright yellow (reaching a plateau within 5 min) in the *p*NPG sample, while no coloration was detected in the L-pNPG sample. This result confirmed that *p*NPG, and likely also L-*p*-NPG substrates, remained intact and that *p*NPG could still be properly hydrolyzed by β-glucosidase.

We also considered the possibility that if present in *H. salinarum*, the β-glucosidase of our microorganism astronauts might not be secreted. To test this, we repeated the experiment using lysed cells (cell lysis was performed by ultrasonication in an ultrasonic bath for 10 min) to release intracellular proteins into the solution. However, no reaction was observed over 15 days, and the addition of almond β-glucosidase again produced the same results as above.

In conclusion, although our assumption that “native-chirality” β-glucosidases hydrolyze only carbohydrate substrates with the natural L-configuration was consistent with the observations, no such enzymatic activity was detected in the *H. salinarum* astronauts, neither with the Earth-borne D-glucose substrate nor the L-glucose mirror image. This finding suggests that *H. salinarum* could serve as a suitable Earth ambassador, safely carrying either D- or L-chirality carbohydrate analogs to probe extra-terrestrial handedness.

Although more difficult to assay, a (commercially available) sweet gift of L-glucose could be considered a “safe” present aboard the starship during the long voyage alongside the *H. salinarum* crew, as it is non-metabolizable by them, while still potentially metabolizable by mirror-image extra-terrestrial organisms.

In contrast, D-glucose is likely a less suitable option; although not proven to be metabolized under our experimental conditions, it is conceivable that our microbial astronauts possess or could eventually evolve metabolic pathways enabling them to utilize it as an energy source.

From a practical perspective, the unprecedented β-L-glucosidase chromogenic probe prepared and rigorously characterized in this study, L-*p*PNPG, could be useful for terrestrial scientists willing to identify and measure β-L-glucosidase activities in terrestrial enzymes yet to be discovered.

Astrobiology and Anthropology as Transdisciplinary Allies

Astrobiology is a relatively young discipline that has thrived since the advent of space exploration and the discovery of exoplanets [Cockell, 2001]. In 1975, NASA launched the Viking program in search of signs of life on Mars, and in 1984, the Search for Extra-Terrestrial Intelligence (SETI) Institute was founded. Astrobiology explores the potential and origins of life in the universe, bridging the scales from the molecular realm of chemistry through the microscopic world of microbiology to the macroscopic domain of planets and galaxies. In this sense, it follows Feynman's spirit, connecting the extremely small with the extremely large [Anniversary of a Myth, 2009] and envisioning a new field of research. Astrobiology also forces a confrontation with our deepest conceptual boundaries, unsettling anthropocentric, terra-centric, and even life-centric assumptions as we recognize that what we seek may lie beyond our present imagination.

This movement between extremes and scale, perspective, and meaning echoes patterns of anthropological inquiry, such as Victor Turner's notion of communitas [Turner & Abrahams, 2017], an intense experience of connection that arises in liminal phases, dissolves hierarchy, and fosters connection. While Turner's original focus was on human participants, recent interpretations have expanded communitas to include non-human agents, materials, and processes, evoking a more-than-human field of shared becoming, where diverse forms of knowing are entangled [Haraway, 2016]. Astrobiology, in its own liminal search, echoes these patterns of entangled knowing, waiting to be forged in an encounter with the cosmic other.

We propose both anthropology and astrobiology as key allies in transdisciplinary collaborations. Anthropology has the tools to examine how different fields construct meaning and knowledge. More than a mode of observation, anthropology enables a situated, relational way of knowing, which is especially valuable when disciplinary boundaries are in flux. In transdisciplinary contexts, it helps track how concepts shift between domains and how language shapes perceptions. Rather than seeking synthesis or consensus, it holds space for tension, ambiguity, and multiplicity. When brought into dialogue with astrobiology, anthropology finds unexpected resonance. Both explore how meaning emerges in radically different contexts. Just as anthropology asks what it means to be human across diverse life worlds, astrobiology asks what it might mean to be alive beyond Earth. In this shared space of speculation and destabilized categories, anthropology reflects on the assumptions embedded in scientific inquiry, while astrobiology stretches its scope beyond the human and terrestrial boundaries.

From Ping-Pong to Pattern: Idea Emergence Between Systems

It was the collaborative process itself that formed the blueprint for the artistic work, as initial ideas for a vessel designed to make contact with potential extra-terrestrial microbial life began to take shape. Co-author Marie Catherine Sforna remarked on the toughness of *M. sedula*, sparking the image of extremophiles as astronauts—survivors, travelers, and cosmic emissaries. Conversations with geologist Frances Westall while exploring and examining the International Space Analogue Rockstore (ISAR)[3] collection further expanded the concept: the vessel design would be based on asteroids, moving away from conventional manufactured forms and inviting alternative ways of thinking about spacefaring objects. Building on this, a discussion with a co-author Sebastian Gfellner introduced the idea of the vessel as a generation ship—or "arkship"— carrying life across cosmic distances. This progression—from envisioning resilient microorganisms as astronauts to shaping the vessel like an asteroid to conceptualizing it as a microbial arkship—traces the project's collaborative evolution. The collaborative progression marks the beginning of what we term the ping-pong phase. While learning and doing intersect, the idea is shaped through quick exchanges, such as hitting a ball made of wet clay back and forth. This is the stage where the artist, while still trying to understand the concept of chirality by making molecular models from plasticine, is already following laboratory protocols to cultivate microorganisms. The pendulum swings from the lab to the studio, from protocol to improvisation, from fact to intuition. This dual movement between scientific inquiry and artistic speculation shapes the emerging narrative gesture (**Figure 8**).

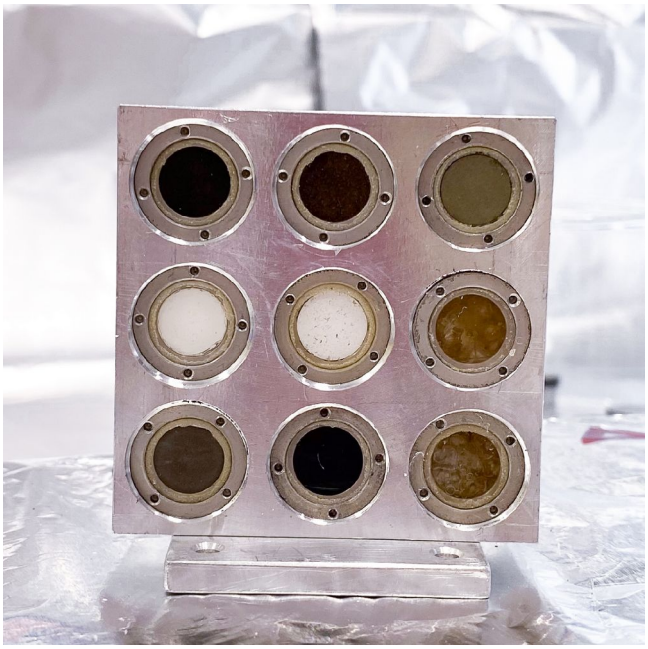

Figure 8: From science to art: Microorganisms grown on various mineral substrates embedded in a space exposure well taken out of the scientific context become an artistic object detached from its original purpose.

[3] http://www.isar.cnrs-orleans.fr/isar/

Finding Analogies: Making Connections

The artist believes that it is essential to follow lab procedures to the best of one's ability to understand their underlying principles as far as possible. This deep engagement with both physical substances and theoretical concepts is not about replication; it serves as a method to evoke the emergence of ideas—moments when synapses connect previously unrelated elements, placing them in an experimental relation. Within this disciplined framework, perceptual shifts occur. The act of counting cells under a microscope becomes an artistic moment: Is it a cell or a mineral fleck? The rhythmic behaviors of magnetic stirrers of various sizes homogenizing culture media at different frequencies may become music. The line blurs. This moment of uncertainty, where data and visual perception intertwine, fuels an artistic process in which the red "Martian" soil from the host institute basement merges with extremophile cultures and minerals, culminating in a visual essay.

These moments of unexpected synthesis mark a shift from scientific observation to artistic play. This is where freedom enters: when the artist stops absorbing and begins transforming and creating meaning, and not just mirroring it.

Beyond Representation: Experimenting and Creating

At one point, co-author Carlo Pifferi said: *"Ah, so you really want to do something, an experiment? I thought this would be more of a representation"*. This shift from representation to intervention marks the point at which art and science begin to actively shape one another, no longer running in parallel but becoming entangled. The speculative narrative of extremophiles as interstellar travelers has become a trigger for real scientific inquiry. This is no longer a mere exchange but a fusion: the artist enters the scientific process to contribute, provoke, and open new pathways. Speculative questions about art can seed experiments that would otherwise never occur. This is the unique role of the artist in science: to ask questions that no scientist would ask, to propose impossible ideas that, through collaboration, become experiments, objects, and new forms of knowledge (**Figure 9**).

Figure 9: Glass object (by Anna Steward) composed of opposing chiral hand forms merges scientific inquiry with an artistic perspective, reflecting the symmetry and otherness of "mirror life".

Exhibition and Performance

The first series of vessels was presented in an immersive installation, envisioned as a deserted, possibly post-human laboratory tent. Suspended in the act of being filled with mineral powders, biopolymer substrates, and microbial samples, the sculptures function as speculative objects—quasi-laboratory artifacts bridging scientific inquiry and artistic imagination. Surrounding elements, including minerals, microbial cultures, and reference materials, provided context, framing the installation as a space for a sensory encounter with speculative questions of astrobiology. A glossary offered an accessible scientific background, further supporting visitor engagement. Building on this initial presentation, a second exhibition is being developed in which chirality will play a central role, extending the project's exploration of asymmetry and mirrored forms in the context of life beyond Earth.

The exhibition opening was accompanied by the performance "Alien in the Closet", a collaborative work between a researcher and an artist (**Figure 10**). Lasting approximately 45 min and set to a live electronic score, the piece choreographs laboratory techniques to narrate the story of microbial explorers from stasis to speculative deployment across the cosmos. In terms of performance, the scientist Sebastian Gfellner enacted the improved extraction protocol developed during previous research [Gfellner et al., 2025a], merging scientific precision with a performative presence. Meanwhile, the artist Anna Steward prepared the chiral metabolic "gift" by pouring biopolymer infused with minerals into Petri dishes, representing the L-glucose offering. In parallel, the microbial astronauts were placed

into cryogenic hibernation, poised for their voyage aboard the arkship. The materials used included Mars-analog material and leftover cell-mineral mixtures from the cell counts of an exposure experiment conducted in a Mars simulation chamber [Gfellner et al., 2025b]. This reciprocal entry—the scientist into the artistic world and the artist into the scientific world —is a foundational aspect of the work. This signifies not only a shift from scientific protocol to a science-fiction narrative but also a profound methodological fusion in which roles became interchangeable. Through this entanglement, performance moves beyond conventional collaboration, proposing a new model for transdisciplinary creation.

Figure 10: Impressions from the performance "Alien in the Closet". Left: Artist Anna Steward preparing a speculative arkship. Right: Scientist Sebastian Gfellner preparing the microbial astronauts for takeoff.

Conclusion

Astrobiology is not primarily about extra-terrestrial life; it is about the nature of otherness itself. This mirrors the authors' artistic practice of discovering strangeness in the familiar, kinship in otherness, and familiarity with the weird. We propose that this orientation toward otherness, whether cosmic, microbial, material, or symbolic, is the underlying principle of transdisciplinary research. Transdisciplinarity is not simply the merging of fields; it is the holding of a shared in-between space in which artists and scientists encounter uncertainty. In this liminal zone—between the empirical and the speculative, the methodical and the intuitive—new inquiries take form. It is a field shaped as much by myth as by method, where knowledge is co-created through encounters, relations, and transformations.

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Author Contributions

A.S., S.V.G., and M.R. conceptualized the project. A.S., S.V.G., and V.A. designed the experiments, and A.S., S.V.G., and M.C.S. cultivated the microorganisms used in this study. A.S. designed and manufactured the artistic objects and conducted the art exhibition. A.S. and S.V.G. designed and implemented the art-science performance. A.S. and S.V.G. designed the manuscript. All authors contributed to the editing and discussion of the manuscript.

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