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From Earth to Space: Macau's role in exploring the new frontiers of mycology

Da Terra ao Espaço: o papel de Macau na exploração das novas fronteiras da micologia

Marta Filipa Simões
State Key Laboratory of Lunar and Planetary Sciences (SKLPlanets), Macau University of Science and Technology (MUST), Taipa, Macau S.A.R., China.
China National Space Administration (CNSA), Macau Center for Space Exploration and Science, Taipa, Macau S.A.R., China.
msimoes@must.edu.mo
marta.simoes.pt@gmail.com.
ORCID: 0000-0002-8767-9487

ABSTRACT

As humanity ventures further into the cosmos, the field of astromycology, which studies the effects of space conditions on fungi, is gaining increasing importance. Fungi, with their remarkable adaptability and ability to thrive in extreme environments, hold immense potential for space exploration. In Macau, a special administrative region of China, the State Key Laboratory of Lunar and Planetary Sciences (SKLPlanets) has emerged as a pioneer in astromycology research. The lab's astrobiology research group is dedicated to understanding the effects of space conditions on fungi and developing new technologies for utilizing fungi in space exploration. Their work includes sampling from terrestrial analogues, conducting exposure experiments with simulated outer space parameters, and screening fungal processes and strains for potential applications in space. Macau's contributions to astromycology are paving the way for ground-breaking discoveries and technological advancements that will shape the future of space exploration.

KEYWORDS

Astromycology, Fungi, Macau.

RESUMO

À medida que a humanidade se aventura mais profundamente no cosmos, o campo da astromicologia, que estuda os efeitos das condições espaciais nos fungos, está a ganhar cada vez mais importância. Os fungos, com a sua notável adaptabilidade e capacidade de prosperar em ambientes extremos, detêm um imenso potencial para a exploração espacial. Em Macau, uma região administrativa especial da China, o Laboratório Estatal de Ciências Lunares e Planetárias (SKLPlanets) emergiu como pioneiro na investigação em astromicologia. O grupo de investigação em astrobiologia do laboratório está dedicado a compreender os efeitos das condições espaciais nos fungos e a desenvolver novas tecnologias para utilizar fungos na exploração espacial. Parte da investigação deste grupo inclui a recolha de amostras de análogos terrestres, a realização de experiências de exposição com parâmetros simulados do espaço, e a triagem de processos e estirpes fúngicas para potenciais aplicações na exploração espacial. As contribuições de Macau para a astromicologia estão a abrir caminho para descobertas revolucionárias e avanços tecnológicos que irão moldar o futuro da exploração espacial.

PALAVRAS-CHAVE

Astromicologia, fungos, Macau.

1. Astromycology in Macau

Macau, a special administrative region of China, is playing a leading role in astromycology research. On October 8th, 2018, the Macau University of Science and Technology (MUST) became the home of the State Key Laboratory of Lunar and Planetary Sciences (SKLplanets, *www.must.edu.mo/en/ssi*), an establishment authorised by the Chinese Ministry of Science and Technology. This is the country's first State Key Laboratory dedicated to astronomy and planetary sciences.

Later on, in December 12th, 2019, "The Macau Centre for Space Exploration and Space Science" was approved by the China National Space Administration (CNSA) and established at MUST. This centre acts as a training ground for researchers, and it is a platform for global scientific interchange and technological collaboration, and a scientific support system for space exploration and science. The lab aims to boost Macau's space industry and is increasingly becoming a major platform for CNSA in the Guangdong-Hong Kong-Macau Greater Bay Area. SKLPlanets established its Astrobiology and Cosmochemistry Experimental Platforms (ACEP), creating the first laboratory dedicated to astrobiology research. The astrobiology research group at the SKLPlanets has part of the team dedicated to astromycology, studying the effects of space conditions on fungi and developing new technologies for using fungi in space exploration.

2. From Astrobiology into Astromycology

The vast expanse of space has long captivated human imagination, beckoning us to unravel its mysteries and seek new frontiers in science and develop new fields of research. The study of astrobiology is still a recent field with only a few decades of existence and of accumulated data/studies. Astrobiology is a multi and interdisciplinary area of research that draws upon the principles of astronomy, biology, chemistry, geology, and physics and that links all these aspects of the several fields with space exploration. It delves into the origins, evolution, distribution, and future of life beyond Earth, exploring the possibility of extraterrestrial life and the conditions that could support it. Astrobiology tries to answer several major questions like: "Are we alone?", "Is life on earth a fluke?", or "Are there other worlds that support life?". There are no straight-forward answers for these, but there are several ways that can help us contributing to find answers. If we are able to 1) plan safer and sustainable missions, and 2) guarantee the best conditions for future space missions, especially crewed missions, and even future bases; we will then be able to explore space in a better way which will facilitate achieving some answers.

Within astrobiology, studies are now increasingly focusing on mycology, therefore, astromycology is now becoming a new research topic. As we venture further into the cosmos, we are faced with the need to develop innovative technologies and understand the effects of extraterrestrial conditions on living organisms. Among the diverse organisms with potential applications in space exploration are fungi – eukaryotic organisms that encompass mushrooms, filamentous fungi commonly referred to as moulds (Fig. 1), and yeasts. Traditionally, mycology, the study of fungi, has been focused on terrestrial ecosystems. However, with the increasing interest in space exploration, and the study of fungi in space environments – Astromycology, has emerged as an important field of research [Simões et al, 2023]. The word "astromycology" became more familiar to the general public with the TV series "Star Treck Discovery". One of the characters, Paul Stamets (fittingly named after a real mycologist), was the spaceship's astromycologist. His job on the series leaned heavily towards fiction; however, astromycology is a real scientific field. Astromycology is a research field that is at the interface between astrobiology and mycology, and that studies terrestrial fungi in space and space conditions [Simões et al, 2023].

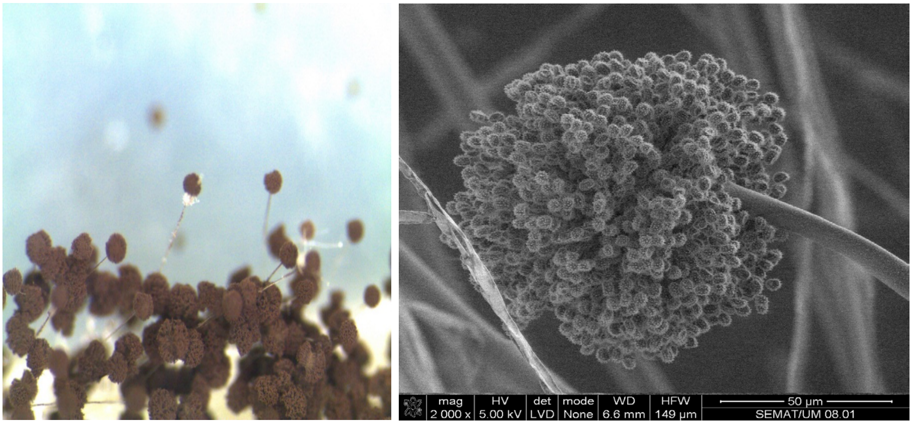

Figure 1. Representative images of a filamentous fungus from the genus *Aspergillus.* Image from stereomicroscopy (left side), image of electron microscopy (right side).

For a long time, mycology itself was an ignored, overlooked, and undervalued field. However, lately, it has been gaining more relevance for several different reasons. Fungi have unique properties that make them well-suited for space exploration, including their ability to adapt to extreme environments. They achieve this through mechanisms like the production of compatible solutes, which help them survive water stress [Magan, 2007], or by encoding specific enzymes (e.g., superoxide dismutases (SOD), catalases (CAT), glutathione peroxidases (GPX), peroxiredoxins (PRX), and glutathione S-transferases (GST)) to assure cellular homeostasis, neutralizing the effects of reactive oxygen species (ROS), and surviving oxidative stress [Segal-Kischinevzky et al., 2022]. Fungi also have an immense potential for bioremediation. For example, white rot fungi are able to break down complex organic pollutants by producing produce enzymes such as the ligninolytic enzymes, being particularly effective in removing pollutants like PCBs (polychlorinated biphenyls) and PAHs (polycyclic aromatic hydrocarbons) from contaminated soil and water [Tomer et al, 2021]. Moreover, fungi have the ability to produce valuable compounds which arises from their genetic makeup, intricate biochemical processes, and their dynamic interactions with the environment. Fungi can produce an extensive variety of secondary metabolites which include nitrogen-containing compounds with various biological activities (e.g., alkaloids), anticoagulant and antioxidant (e.g., coumarins), anti-inflammatories (e.g., flavonoids), antimicrobial and immunomodulators (e.g., saponins), essential oils (e.g., terpenes), pigments (e.g., melanin), and many different enzymes [Keller et al, 2005; Devi et al, 2020; Santomartino et al, 2023; Tsivileva et al, 2023].

2.1 From terrestrial fungi to the cosmic realms

Fungi, ubiquitous on Earth, have demonstrated remarkable adaptability and plasticity, thriving in some of the most extreme environments on our planet [Gostinčar *et al.* 2022]. They have been found flourishing in the frigid soils of Antarctica, where the desert areas mimic those on Mars [Selbmann *et al.* 2015]; the scorching heat of Yellowstone National Park's hot springs, which offer insights into chemical reactions and the origins of life [Bazzicalupo *et al.* 2022]; and the highly acidic waters of volcanic lakes, which are intersections of magmatic-hydrothermal systems where we can study certain processes similar to those existing in other planetary bodies (e.g., degassing, hydrothermal, and volcanic) [Russo *et al.* 2008]. Fungi have also been isolated from high radiation areas, such as the Chernobyl Atomic Energy Station, with many of these showing increased growth under exposure to ionizing radiation [Zhdanova et al, 2004; Dadachova & Casadevall, 2008]; and locations with altered gravity, such as space stations (e.g., International space station – ISS [Checinska Sielaff et al, 2019], Mir station [Makimura et al, 2001], and China Tiangong-1 space station [Yang et al, 2020]).

This remarkable ability to endure and thrive in extreme conditions suggests that fungi possess the resilience to survive and even flourish in the harsh environments of space. Furthermore, several researchers have studied fungi under simulated and real space conditions and many of the parameters common in many outer space locations (such as microgravity, galactic cosmic radiation, solar UV radiation, vacuum, low water activity, exposure to regoliths) have been studied on many different fungal species. However, much is still to be investigated as can be read in [Simões et al, 2023] and many other fungal species need to become focus of research. Considering that, according to recent estimations, we only know about 3 to 8% of all fungal diversity on our planet [Simões et al., 2013], much more research needs to be done.

Understanding fungal development and adaptation to outer space conditions is also highly relevant when discussing planetary protection, both in terms of forward contamination (the transference of life and other forms of contamination from Earth to another celestial bodies, originating from, e.g., microbial resources taken with specific purposes, as well as unaccounted hitchhikers or even crews' microbiomes) and backwar contamination (the introduction of extraterrestrial organisms and other forms of contamination into Earth's biosphere) [Simões & Antunes, 2021; Benardini & Moissl-Eichinger, 2022]. Fungi have several mechanisms useful in their adaptation to stressful or extreme condition, enabling them to survive them to adapt and survive outside our planet. These include hypoosmotic stress management (e.g., mechanosensitive channel proteins help manage hypoosmotic stress related to microgravity), increased DNA repair activity to counteract radiation exposure, mobile genetic elements which enhance metabolism, and potential pathogenic traits (e.g., small molecule and peptide synthesis and ATP-dependent transporters, have evolved in ISS microorganisms) [Szydlowski et al, 2023]. These adaptations may explain why microbes exposed to space conditions demonstrate enhanced antibiotic resistance and pathogenicity. Fungal species with new and developed characteristics acquired while in space can also be considered a form of backward contamination [Moissl-Eichinger et al, 2016].

2.2 Unique properties of fungi with potential impact for space exploration

Fungi can be considered from very different perspectives. They can be regarded as foes, mostly because they can produce mycotoxins; they can cause allergic reactions, spoilage, decomposition, and infections in humans and other animals, as well as in plants (phytopathogenic) and insects (entomopathogenic). One example of the increased relevance of fungi within this context is the World Health Organization's (WHO) fungal priority list divulged in October 2022 (*www.who.int/publications/i/item/9789240060241*). This list identifies critical fungal species and provides potential actions perceived as highly important or even crucial to human health regarding infections caused by these fungi. The goals of this document include advocating for enhanced public health interventions, research and innovations, as well as for improved and more efficient surveillance in terms of diagnostics and antifungal resistance monitoring [Fisher & Denning, 2023].

Conversely, some fungi can also be considered the best of friends, e.g., the non-pathogenic species belonging to the fungal genera *Aspergillus*, *Penicillium*, and *Saccharomyces* [Kour et al, 2019], since they are associated with numerous helpful production processes (Fig. 1) and biotransformation processes (e.g., yeast fermentations, production of bread and alcoholic beverages). Fungi can produce many different types of metabolites (e.g., antibiotics, antifungals, anti-tumorals, plant growth hormones, immunosuppressive agents, cholesterol lowering drugs), and many different types of enzymes (e.g., for industry, and food products – cheese, tempeth) [Hyde et al, 2019]. We can use their biomass as food (e.g., mycoprotein), and take advantage of them for biological control (of insects and nematodes), or in forestry and agriculture (e.g., through mycorrhizal associations); and, we can even exploit them for different mycosynthesis processes like the production of metallic nanoparticles [Ottoni *et al.*, 2017; Simões *et al.*, 2020a].

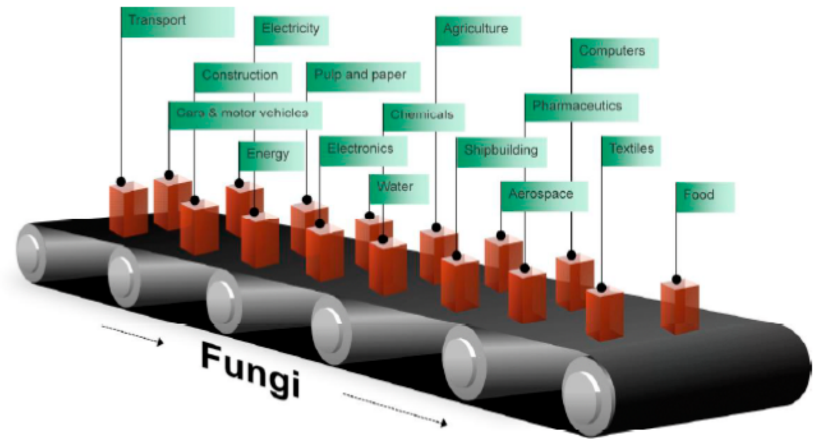

Figure 1. Production processes supported by fungi [Simões *et al.*, 2023].

Filamentous fungi have been our companions in space exploration since the first steps into space. They were the cause of malfunctioning in the first modular space station initially operated by the Soviet Union and later by Russia, Mir, where they started to grow, eventually covering up the windows and control panels. Species such as *Aspergillus* spp., *Penicillium* spp., and *Cladosporium* spp. where isolated at several time points of sampling and also once the station was returned to our planet in 2001 [Viktorov *et al.* 1998a, 1998b; Makimura et al, 2001; Novikova *et al.* 2001].

Regardless, all of these the fungal products, technology, and applications used in industry and daily life on Earth can be directly transferred and applied to space exploration [Wösten *et al.*, 2018; Cortesão *et al.*, 2020; Ferretti *et al.*, 2020]. The 2030 Agenda for Sustainable Development of the United Nations lists 17 Sustainable Development Goals (SDGs), which support environmental, social, and economic sustainability. Astromycology and space exploration can help us achieve these SDGs. This can happen by using diverse fungal processes and products, harnessing mycological technology, and implementing innovative fungal applications [Meyer *et al.*, 2020; Koehle *et al.*, 2023]. These contributions are wide-ranging and include areas such as global health, water management, energy solutions, and urban development initiatives [Meyer *et al.*, 2020]. By taking a comprehensive approach that includes policy, strategy, and technology, astromycology can be a key player in reaching the SDGs [Meyer *et al.*, 2020; Simões *et al.*, 2023]. For example, fungi can be used to create biofuels, which can contribute to clean energy solutions. They can also play a role in waste management, helping to recycle organic matter and reduce pollution. Furthermore, certain fungal species can be used in the production of antibiotics, contributing to global health goals. In the context of space exploration, fungi can be used in life support systems, where they can help recycle waste and produce food and other useful materials. This makes astromycology a crucial field for future space missions and colonization efforts.

3. From field studies to space exploration

The SKLPlanets Astrobiology team, at MUST, in Macau, is involved in many scientific endeavours. Their multifaceted research threads intertwine sampling from terrestrial analogues, exposure experiments with simulated outer space parameters, and a focus on space biotechnology with screening of different fungal processes under selected simulated outer space conditions, and screening of new isolated fungal strains and species (mostly from extreme environments) for the production of different products and in some cases their incorporation into new materials (e.g., incorporation of mycogenic metal nanoparticles in textiles and cement).

3.1. Sampling from terrestrial analogues

Across our planet there are many locations, as for example the ones listed in Table 1, where scientists study features that may be considered comparable (or analogous) to those on other worlds. These are known as: terrestrial analogues. Studying these types of locations is essential to support for the search for life beyond Earth, to define habitable environments on other worlds, and to serve as reference of extreme environments and survival strategies. Understanding life in these locations is one of the main research lines within astrobiology.

Table 1. Selected examples of terrestrial analogue sites for Mars on Earth (adapted from Preston & Dartnell, 2014).

Analogue sites for Early Mars:	
Rio Tinto	Spain
Yellowstone Park	USA
Dongwanzi Ophiolite Complex	China
Analogue sites for Middle Mars:	
Beacon Valley	Antarctica
Sub-glacial Volcanism	Iceland
Kilimanjaro	Tanzania
Analogue sites for Present Mars:	
Atacama Desert	South America
Antarctic Dry Valleys	Antarctica
Qaidam Basin	China
Analogue sites for Europa and Enceladus:	
The Mariana Trench	Pacific Ocean
Lidy Hot Springs	USA
Columbia River Basalts	USA

Within those places, the research team from MUST is involved in the analyses of samples from:

- different salterns (terrestrial analogues for early Mars due to their aridity, high solar irradiance, salinity, and oxidation [Barbieri and Stivaletta, 2011]), in

Portugal (Aveiro and Rio Maior), Cabo Verde (Boavista, Maio and Sal islands) (Fig. 2), and also in Slovenia (Sečovlje) (Fig. 3).

Figure 2. Pedra de Lume Salterns, inside an extinct volcano crater, Sal Island (Cabo Verde).

Figure 3. Man-made solar salterns in Sečovlje (Slovenia).

- Lake Tírez in Spain (Fig. 4), an inland hypersaline lagoon considered an analogue to the salt deposits of Mars as well as its wet-to-dry transitions [Fairén *et al.*, 2023] and to the briny ocean of Europa (one of Jupiter's moons, with an icy surface and a subsurface ocean of liquid water which has become the focus of many space missions and space exploration research) due to its hypersaline brines rich in magnesium (Mg), sodium (Na), and chlorine (Cl) [Prieto-Ballesteros *et al.*, 2003; Preston & Dartnell, 2014].

Figure 4. Lake Tírez (La Mancha, Central Spain).

- Red Sea brines, deep-sea sediments, and hydrothermal vents which can be analogues for oceans in the icy moons of the outer solar system [Antunes et al, 2020]. For these, all samples were collected during the expedition M194 Hexplores, onboard the research vessel (RV) METEOR (Fig. 5), and using a remotely operated vehicle (ROV) Kiel 6000 from GEOMAR, through a collaboration with King Abdullah University of Science and Technology (KAUST), Saudi Arabia.

Figure 5. Research vessel (RV) METEOR (left side); samples being collected with a slurp gun of a remote operated vehicle (ROV) at the bottom of the Red Sea (right side).

- hot springs from Deception Island, Antarctica (Fig. 6), more specifically water and sediments. This island is a marine stratovolcano with extreme steep temperature gradients, with active fumaroles that can reach temperatures up to 100 °C, and a great part covered in glaciers. This location represents a great terrestrial analogue for Mars's extinct volcanoes and Enceladus's cryovolcanoes [Bendia et al, 2018]. In particular, Mars likely had hydrothermal activity in the past, and studying this location can help us understand the potential for subsurface Martian life.

Figure 6. Research station, Gabriel de Castilla Base, located on Deception Island, South Shetland Islands, Antarctica (photo credit: André Antunes).

Many of the locations studied have extreme conditions such as freezing temperatures, strong winds, and limited sunlight. They mimic in many ways several outerspace locations, like Mars or Europa. For examples, if we consider Mars, it is a frigid place, with thin atmosphere, extreme cold, and dust storms. Studying how life (including extremophiles) adapts to Deception Island's environment provides insights into potential Martian habitats.

3.2. Exposure experiments to simulated outer space parameters

Spacecraft, space stations, and shuttles have closed environments that allow the performance of many different mycological experiments and have been used for mycological testings (e.g., [Knox *et al.* 2016; Blachowicz *et al.* 2019; Romsdahl *et al.* 2019, 2020]). Understandably, such experiments with exposure to real space conditions are somewhat limited and conducted in small numbers. Not all researchers have access to space facilities or outer space environments, and concerns regarding biological load are always too wide-scoped and with a very limited focus on fungi. Testing under simulated conditions is an alternative more accessible to astrobiology research. However, certain space parameters are not easily simulated in a regular microbiology lab. When it comes to gravity, the majority of fungal assays has been done under microgravity (e.g., [Purevdorj-Gage *et al.* 2006; Altenburg *et al.* 2008; Yamazaki *et al.* 2012; Sathishkumar *et al.* 2014, 2016; Jiang *et al.* 2019]); and all with a limited number of species [Simões *et al.* 2023].

Regardless, experiments involving exposure to simulated outer space conditions, have been developed by the SKLPlanets team, focusing on the following: simulated microgravity (SμG) using a 3D-clinostat (Fig. 6), simulated hypergravity, attained with the same clinostat used for SμG (for 2-3 G); and, through the use of a Large Diameter Centrifuge (LDC, Fig. 7), available at the facilities of the European Space Research and Technology Center (ESTEC), Noordwijk, the Netherlands, which the Macau research team was able to access through the HyperGES programme. HyperGES is a cooperation programme between the United Nations Office for Outer Space Affairs (UNOOSA) and the European Space Agency (ESA), developed under the Access to Space for All Initiative. For the LCD, the experiments done focused on 10G and 15G values of hypergravity.

Figure 6. 3-D Clinostat from Gravite (image from www.asone-int.com/2017/06/22/gravity-controller-gravite/), available at the Macau University of Science and Technology (MUST), Macau S.A.R., China.

Figure 7. Large Diameter Centrifuge (LDC), available at the European Space Research and Technology Center (ESTEC), Noordwijk, the Netherlands.

We have now experimented several microbial species on both equipment (Fig.s 6 and 7.) under several different projects. For the first, the clinostat (Fig. 6), which we explore on a daily basis, we have developed several projects: 1) "Simulated microGravity effects on Fungal Genomics – GFG", developed in collaboration with our collaborators from Turin University, Italy; 2) "MBF_SpacEx – Medical and Biotechnological potential of Fungi for Space Exploration", a project supported by MUST; 3) "Ice on Fire: Bioprospecting extremophiles in Antarctica's Deception island geothermal sites", funded by Applied Microbiology International (AMI, https://appliedmicrobiology.org/); and, 4) "Mitigating Outer-planetary Risks: Fungal Adaptation in Space exploration - M.O.R.SpaceEx", funded by the Science and Technology Development Fund (FDCT). The latter is still ongoing.

For the LCD (Fig. 7), we developed the project "HyperSpacEx – Medical and Biotechnological potential of Fungi in Hypergravity for Space Exploration" through a 2023 HyperGES fellowship. The samples exposed under hypergravity (10G and 15G) were selected fungal species and this data is still being processed.

We have been focusing on both of the parameters, microgravity and hypergravity, because they are both relevant under the space exploration context and it is widely known that these are conditions that can alter cells and microorganisms in several different ways. However, fungal species have been understudied, especially for hypergravity making this a knowledge gap that need filling. Moreover, to the best of our knowledge, only two fungal species were tested under this parameter: 1) *Flammulina velutipes*, a fungal species belonging to the Basidiomycota phylum, tested at 20G, and showing a differential enlargement of the lower side of the stipe with the accumulation of cytosolic vesicles proving morphological alterations after exposure [Kern and Hock 1996], and 2) *Neurospora crassa* which showed a higher growth rate under hypergravity Pence *et al.* [1992].

It is known that hypergravity has many implications in other organisms. Pedrozo et al [1996] showed that *Aplysia californica*, species of sea slug, among several physiological changes, grew faster when exposed to 2, 3, and 5.7G. Dos Santos *et al.* [2016] grew arugula (*Eruca sativa*) under 7G, having an 18% increase of plant mass and a resulting essential oil with antifungal activity different from the one obtained from the control sample (without exposure), which showed different chemical composition, therefore a different production of secondary metabolites. Le Bourg et al [2009] tested flies infected with fungus *Beauveria bassiana*, under 3 and 5G but no analysis were published on the fungal species.

3.3. Space biotechnology

Screening of different fungal processes under selected simulated outer space conditions

Many are the mycological processes with potential to aid and contribute to space exploration, as already mentioned in section 2.2. Many fungal-based products include antibiotics and other antimicrobials, bioethanol, biofertilizers, biofuels, enzymes, food colourants, organic acids, pharmaceuticals, platform chemicals, proteins, and vitamins [Hyde et al, 2019; Cortesão et al, 2020]. Some of these can have direct application on many different areas, from agriculture, to biotechnology, and day-to-day life; and, all of these can be directly transferred for applications in space and also for future colonization programs [Santomartino *et al.*, 2023]. For example, space agriculture is a potential area of application that has gained significant attention in recent years. Bioregenerative Life Support Systems (BLSS) will be essential for future crewed missions, and many studies have been developed on this topic. These systems aim to mimic Earth's biosphere functions to provide life-sustaining resources such as food, water, and oxygen to astronauts during long-duration space missions. The concept of BLSS involves the cultivation of plants and microorganisms in a closed environment, where waste products are recycled and used as inputs for plant growth. This creates a symbiotic relationship between the crew and the life support system, similar to the natural ecological balance on Earth, and involves another specific and fundamental symbiotic relation, between fungal species and plant species, which might be affected by space conditions [Duri et al, 2022]. For instance, certain fungi that form mutualistic relationships with plants, aiding in nutrient uptake and providing resistance against diseases, might adapt and be altered in a way that allows them to better promote plants growth. Regardless, a microgravity environment, and exposure to cosmic radiation in space could potentially alter these relationships, affecting plant growth and health and consequently the human crewmembers. Moreover, the use of regolith (the layer of loose, fragmented material covering solid rock on celestial bodies like the moon and Mars) as a growth medium for plants presents its own set of challenges. Regolith lacks the organic matter and nutrients found in Earth's soil, and its properties can vary greatly depending on the location [Zhou et al, 2020]. Research into how plants and fungi interact in these novel conditions is crucial for the success of space agriculture. While space agriculture presents as a promising solution for sustaining long-term space missions, research within this topic is still in its early stages.

A group of fungi with high potential for space applications and for *In situ* resource utilization (ISRU), is the extremophilic and highly melanized fungi which tend to survive high levels of radiation. These fungi have high levels of melanin, a secondary metabolite which is a natural pigment and has several relevant functional properties: anti-radiation, anti-oxidation, photoprotection, biosorbent, and antibacterial effect [Liu et al, 2022]. Two of those species are *Aureobasidium pullulans* and *Knufia chersonesos*, black fungal species, which produce enzymes to degrade plasticised polyvinyl chloride (PVC) and dioctyl adipate plasticizers, and synthetic copolymer polybutylene adipate terephthalate (PBAT), respectively [Koehle et al, 2023]. But, many others can prove to be a good astromycology focus for further research.

Screening of new isolated fungal strains and species for different products and incorporation into new materials

One way to better understand how life can adapt to outer space conditions, and to even develop methods to recognised any life within these environments, is to study life that thrives in terrestrial analogues (e.g., Table 1). For this, we try to know all details regarding microbial life, especially fungal life (within the context here mentioned of astromycology), living in the harsh locations in our planet. We try to understand the fungal communities thriving there and we isolate fungal strains which we characterise in detail. Many of these are new species to science, and they have a high potential of having characteristics that we'll be able to explore in our benefit. Within these isolates' characterisation, part of the research focuses on fungal products (e.g., enzymes, antibiotics, antifungals, biosurfactants, and metal nanoparticles) and therefore on bioprospection.

Metal nanoparticles (MNPs) produced by fungi, or mycogenic MNPs, are a great part of the research focus at SKLPlanets. These MNPs have sparked interest in various scientific fields, including astromycology, due to their unique properties and potential applications.

Fungi, with their remarkable ability to adapt to extreme conditions, are known to play a crucial role in biogeochemical cycles. They have the ability to precipitate various metal ions from their environment, leading to the formation of MNPs. The mycogenic MNPs exhibit unique physicochemical properties, like high stability, biocompatibility, and diverse morphology, which make them more suitable for many applications when compared to chemically produced MNPs [Simões et al, 2020a, 2020b]. Some of these potential applications could be: 1) to have these MNPs serving as radiation shields, protecting other life forms in space environments; 2) to incorporate fungi in bioremediation processes of space habitats, by precipitating toxic metal ions, producing MNPs and thus reducing their toxicity. However, the ability of fungi to produce these nanoparticles under extreme conditions needs to be better studied and explored as an indicator of the potential for life in extraterrestrial environments.

Further research in this area could not only lead to novel applications but also deepen our understanding of life's adaptability and resilience in the face of extreme conditions. The cosmos may be vast and inhospitable, but through the lens of astromycology, it becomes a field of endless possibilities.

At MUST, the SKLPlanets research work is focused on the fungal development in simulated conditions and exposure to artificial regoliths. Selected strains are exposed to the different conditions simulated at the SKLPlanets lab facilities and then screened for their enzymatic profiles and secondary metabolites, with antimicrobial activity, and also for the production of MNPs. Many of the fungal products screened are then researched further and some even incorporated into new materials such as metal nanoparticles incorporated in: 1) textiles, 2) new concrete formulations and 3) drinking-water disinfection systems. Many of the screenings are developed with the support of collaborators, both internal (from MUST), as well as external and international. Below are the main collaborators currently involved in ongoing work:

Algeria: University of Ain Témouchent.
Brazil: Biosciences Institute, São Paulo State University (UNESP).
Brazil: School of Pharmaceutical Sciences, University of São Paulo (USP).
Cabo Verde: Jean Piaget University of Cape Verde (UniPiaget).
China: Institute of Microbiology, Chinese Academy of Sciences Beijing. University of Science and Technology Beijing.
Germany: German Aerospace Center (DLR), Cologne.
India: Atomic Molecular and Optical Physics Division, Physical Research Laboratory, Ahmedabad.
Italy: University of Turin, Turin.
Japan: Earth–Life Science Institute (ELSI), Tokyo Institute of Technology.
Macau: Macau University.
Macau: University of Saint Joseph.
Portugal: Aveiro University, Aveiro.
Portugal: National Health Institute Dr. Ricardo Jorge, Lisbon.
Saudi Arabia: King Abdullah University of Science and Technology (KAUST), Thuwal.
Slovenia: Biotechnical Faculty, University of Ljubljana, Ljubljana.
UK: Edge Hill University, Ormskirk.
UK: School of Physics and Astronomy, University of Edinburgh, Edinburgh.
United Arab Emirates: Center for Space Science, New York University, Abu Dhabi.

InCites (https://incites.clarivate.com) reports that between 2018 and 2023, international collaborative papers from the Astromycology research team accounted for 81.82% of the total. Among these, 75% were concentrated in several disciplines: microbiology, astronomy and astrophysics, geosciences, multidisciplinary fields, and environmental sciences.

According to SciVal (www.scival.com) data analysis on international collaboration, the Astromycology research team from SKLPlanets develops highly collaborative research. From 2018 to 2023, 77.8% of the Astromycology research team papers across all disciplines included in Scopus (www.scopus.com) were produced in international collaboration. The breakdown by discipline is as follows: Medicine – 83.3%, Immunology and Microbiology – 80.0%, and Biochemistry, Genetics and Molecular Biology – 75.0%. These data highlight the extensive international collaboration in SKLPlanets. This trend underscores the global nature of scientific research and the importance of international cooperation in advancing knowledge in these disciplines.

Astromycology is in its initial development and implementation as a research field, with increasing interdisciplinary research being done every day. In the near future it will start providing more and major contributions to astrobiology, space biotechnology, Mars exploration, space exploration, and ISRU; and, Macau research team is setting itself to be a leader in this area.

4. Concluding remarks

As we continue our journey into space, fungi offer a wealth of possibilities and opportunities for advancing space exploration and unlocking the secrets of the universe. Their adaptability to extreme environments and stress conditions, bioremediation capabilities, and production of valuable compounds make them indispensable allies in our quest to understand and explore the vastness of space. Astromycology is a burgeoning field and Macau is at the forefront of its research. Considering all the current developments in applied mycology and fungal biotechnology, coupled with the increase of the bio-based circular economy and sustainable fungal production processes, we can expect revolutionary discoveries and technological breakthroughs. These developments will undoubtedly shape the future of our planet and space exploration. As Meyer *et al.* [2020] noted, fungi have applications in "food, feed, chemicals, fuels, textiles, and materials for construction, automotive and transportation industries, furniture, and beyond".

Furthermore, the research work at the SKLPlanets, at MUST, aligns well with the global infrastructure development strategy adopted by the Chinese government in 2013, the "One Belt One Road" (OBOR) initiative, also known as the Belt and Road Initiative (BRI). This initiative seeks to advance interregional connection and economic development, and the SKLPlanets contributes to these goals by fostering interdisciplinary and global cooperation, advancing economic growth and innovation, identifying applications in relevant industries, and endorsing sustainable practices.

The research at SKLPlanets is innovative, focusing on astromycology and the development of new materials (e.g., by incorporating MNPs). These innovations can stimulate economic growth, a primary key goal of the OBOR initiative/BRI. The incorporation of mycogenic MNPs into textiles, new concrete formulations, and drinking-water disinfection systems has wide-ranging applications in vital sectors like manufacturing, construction, public health, and space exploration. This contributes to economic development, which is another central aim of OBOR initiative/BRI, as is the focus on sustainable development. The SKLPlanets' research also promotes sustainable practices, such as the green synthesis of mycogenic MNPs

In summary, understanding fungal biodiversity in extreme environments and any phenotypical or genotypical changes following exposure to space parameters, or extreme conditions, will undoubtedly benefit the future of biotechnology and space exploration. Mycological research on the effects of outer space parameters, such as microgravity (real or simulated), is poised to usher in a new era in biotechnological research, paving the way for a brighter future for upcoming generations.

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