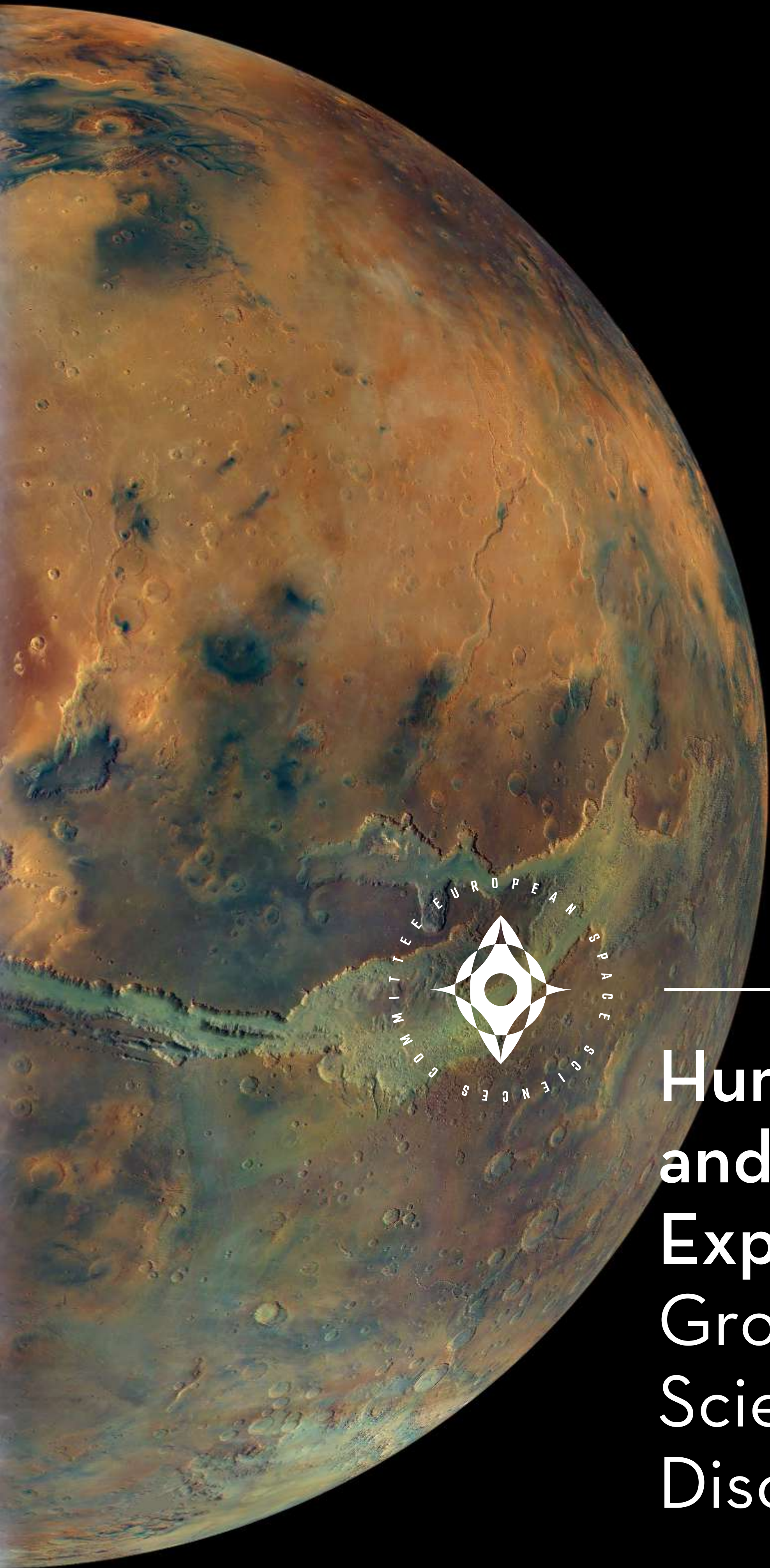


European Space Sciences Committee

# Human and Robotic Exploration

Groundbreaking Science Discoveries

*This document was prepared by the Life and Physical Sciences and Solar System Exploration Panels of the European Space Sciences Committee in response to the ESA contract 5001041653 entitled "Ground-breaking science discoveries and successes associated with ESA Human and Robotic Exploration".*

*Front cover showing a colour-referenced mosaic of Mars produced by Mars Express and the High-Resolution Stereo Camera (HRSC) team, and back cover featuring an amateur photography of the International Space Station transiting the Moon.*

# Table of Contents

# Foreword

From the earliest telescopes to modern space missions, space exploration has always been about extending human curiosity into places we cannot easily reach. Today, the European Space Agency's Human and Robotic Exploration (HRE) programme takes that same ambition into orbit and across the Solar System, combining the strengths of both astronauts and advanced robotic systems. The aim is to gather scientific knowledge, and to develop the tools, skills, and partnerships that will make deeper space exploration possible. The HRE projects range from long-term research aboard the International Space Station (ISS), to robotic spacecrafts studying the Moon, Mars, and beyond, each contributing pieces of a much larger puzzle about our origins, our present and our future in space.

Human spaceflight offers capabilities that no robot can yet match. Astronauts can adapt quickly to changing conditions or unexpected events, carry out complex tasks, and apply human judgement in real time. Working aboard the International Space Station (ISS) and, in the future, on the Moon and Mars, astronauts are the human face of space exploration, conducting experiments, and also assembling and maintaining infrastructures. Life and physical sciences research in these extreme environments yield benefits for people on Earth, from new medical insights to advances in materials science and engineering. On the other hand, robotic missions travel to locations where humans cannot go. They can endure harsh space conditions for years, operate far from Earth without life-support systems, and carry specialised payload to study planetary surfaces, and atmospheres. From orbiters mapping the geology of Mars to landers probing the lunar regolith, robotic systems gather data that help select landing sites, and answer fundamental scientific questions. The greatest impact comes when astronauts and robotic missions are integrated, making space exploration safer, more efficient, and scientifically richer. The HRE also plays a role beyond pure science, as it drives innovation; many of its developments find applications outside the space sector—in energy, transport, healthcare, and environmental monitoring. The HRE Science Discoveries offers a glimpse into the research made possible by European human and robotic missions. Rather than focusing on a single discipline, it spans work in low Earth orbit, on other celestial bodies, and in ground-based analogues, showing how each contribute into the larger goal of space exploration. The projects featured reveal how materials behave in microgravity, track how living organisms respond in extreme environments, and map the landscapes and conditions of other extraterrestrial worlds. Together, they tell the story of how Europe turns complex space missions into lasting scientific and technological gains.

Over the next decades, the boundaries between human-led and machine-led missions will become increasingly blurred. Spacecraft and surface systems will act with greater independence, while astronauts focus on the tasks that demand creativity, and rapid response and adaptation. Robots might explore unknown terrain, or manage routine operations, freeing crews to concentrate on high-priority science. Likewise, humans will oversee and fine-tune robotic activities, ensuring that the work on distant worlds stays aligned with mission goals. For Europe, investing in this partnership is more than a technological choice. It is a way to ensure that our researchers, industries, and scientific institutions remain at the forefront of discovery and exploration, as humanity moves further into the Solar System.

**Zita Martins**
Astrobiologist, Associate Professor,
and Vice-President for International Affairs,
Instituto Superior Técnico (IST),
Universidade de Lisboa, Portugal

# Introduction

Recent advances in neuroscience reveal that the human brain does not merely passively observe the world – it actively probes its environment through movement, experimentation, and an innate drive to explore. Curiosity is not optional; it is a biological imperative, hardwired into our neural circuitry to ensure survival, innovation, and progress. From our earliest ancestors venturing beyond local horizons to the pioneers of science and industry, exploration defines what it means to be human.

Today, having mapped and mastered Earth's frontiers, humanity's next inevitable step is the robotic and human exploration of nearby space. This is not a speculative endeavour but a necessary evolution – one that promises transformative returns. By expanding into the solar system, we unlock unprecedented scientific discoveries, safeguard our future through access to strategic off-planet resources, and catalyse a new economic paradigm with industries ranging from satellite servicing and orbital infrastructure development to asteroid mining.

This brochure showcases Europe's groundbreaking scientific discoveries enabled by its participation in the International Space Station and its pioneering work in astrobiology and the exploration of the Moon and Mars. Compelling as they are, they represent only a foretaste of the advances to come.

Space is the ultimate laboratory. Its microgravity, extreme temperatures, and radiation exposure enable breakthroughs unobtainable on Earth – from revolutionary pharmaceuticals and materials to quantum physics and AI-driven robotics. There is no analogue. The very act of overcoming these challenges accelerates technologies with immediate terrestrial applications: miniaturised medical devices, disaster-resistant infrastructure, and sustainable closed-loop life-support systems.

But leadership in space is not guaranteed. As China and the U.S. race to establish lunar bases and footprints on Mars, secure resource rights, and dominate orbital infrastructure, Europe faces a stark choice: invest now or cede strategic autonomy. ESA's Human and Robotic Exploration programme is not just a scientific endeavour – it is a gateway to sovereign technology, high-value jobs, and a voice in shaping humanity's future beyond Earth.

The question is no longer whether we can afford to act, but whether we can afford inaction. History rewards pioneers. By uniting behind ESA's programme at CM25, Member States can ensure they not only participate in this new era but play a leading role – delivering scientific mastery, economic resilience, and inspiration for generations to come.

The time to commit is now.

Prof. Chris Rapley CBE MAE
Chair, European Space Sciences Committee

# ESA Perspectives

I am pleased to present this brochure highlighting some of the most impactful scientific results enabled by ESA's Human and Robotic Exploration (HRE) programme.

After seeing the excellent example set by ESA's Earth Observation Directorate, we were keen to support a similar effort in the exploration domain. I'd like to commend the European Space Sciences Committee (ESSC), and in particular its Life and Physical Sciences Panel as well as the Solar System and Exploration Panel, for capturing so clearly the impact and diversity of science related to exploration.

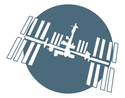
The science conducted within ESA's Human and Robotic Exploration Directorate, referred to as Exploration Science, spans two complementary streams. Exploration focused science is mission-driven research that delivers the actionable knowledge required for safe and sustainable exploration. It is closely tied to the development of technologies, mission systems, and operational tools, and supports the successful implementation of exploration goals. Exploration enabled science, on the other hand, is community-led and curiosity-driven, advancing fundamental and applied research by making use of ESA's exploration infrastructure and data. It addresses broad scientific questions, from the effects of spaceflight on biological and physical systems to the search for signs of life beyond Earth. Together, these two streams ensure that science is both a driver and a beneficiary of human and robotic exploration.

As ESA enters a new era of human and robotic exploration, with a strong focus on European autonomy across low Earth orbit, the Moon, and Mars, Explore2040 places science at the core of its vision. We are committed to uplifting science, embedding it more deeply into future missions. With continued support from the scientific community, bold goals endorsed by ESA's Member States, and strong international partnerships, we will unlock new knowledge for Europe and for the benefit of all.

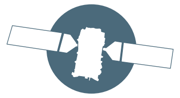
**Daniel Neuenschwander**
Director of Human and Robotic Exploration, European Space Agency

# European Infrastructure, Global Impact: The ISS and Beyond

## How European cooperation has built bridges in orbit, and shaped the future of exploration



ISS



TRAS GAS ORBITER

### A HISTORY OF COLLECTIVE EXPLORATION

The very foundation of the scientific method rests on openness; on the comparison, critique and synthesis of ideas across borders and backgrounds. In space research, where the questions are vast and the technologies complex, cooperation is essential. As ambitions grow toward the Moon, Mars or beyond, so do the risks, costs and opportunities. Collaboration within Europe and with international partners is essential to mitigate these risks, ensure resilience and accrue the benefits. Space science was born in the heat of geopolitical competition, yet even at the height of the Cold War, scientists recognised a deeper truth: knowledge offers common ground. In 1986, an international flotilla of spacecraft was sent to Halley's Comet. ESA's Giotto mission relied on trajectory data from Soviet spacecraft to navigate a daring fly-by, returning humanity's first close-up images of a comet nucleus. This was not only a scientific triumph, but a symbol of diplomacy through shared endeavour.

### THE ISS AS A MODEL FOR SHARED COLLABORATION

Europe's place in human spaceflight has been shaped by cooperation from the beginning. ESA's development of Spacelab provided a unique research capability to NASA's Shuttle programme and gave scientists access to long-duration experimentation in microgravity, laying both the technical and scientific foundations for future endeavours. Bilateral partnerships with Russia through its MIR station further prepared European institutions for what was to come.

The International Space Station represents the high-water mark of these efforts. Conceived by five major spacefaring partners (the United States, Russia, Europe, Japan and Canada) the ISS has become the largest and most intricate engineering project ever attempted in space. Europe's contribution is foundational. ESA delivered the Columbus laboratory, the Automated Transfer Vehicle, the European Robotic Arm and the station's Data Management System. It also provided vital connecting modules, including Harmony and Tranquility, and the iconic Cupola viewing window. These components were not purchased but traded. In a marketplace above Earth, each partner offered its best to serve the whole.

The reward is access, not only to the station itself but to human spaceflight. To date, 19 European astronauts have completed 31 missions to the ISS, with 6 serving as station commander. Through ESA, Europe has deployed sophisticated scientific equipment ranging from the Fluid Science Lab FSL, the Electromagnetic Levitator EML to the KUBIK biological incubators or the cold atom physics payloads such as the Atomic Clock Ensemble in Space (ACES), launched in 2025.

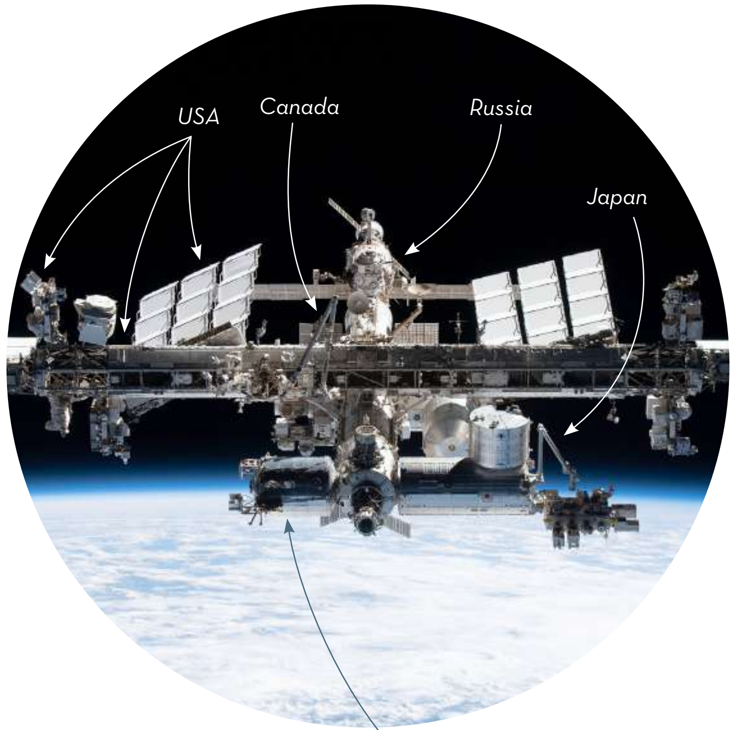
Just as critical is the ISS's commitment to open science. Experiments are peer-reviewed and frequently led by European researchers. Crew time and resources are distributed across partners, maintaining balance and scientific excellence.

### LOOKING FORWARD

Europe's role in future exploration is already taking shape. ESA has placed its first instrument on the Moon (NILS) and operates Mars orbiters like the Trace Gas Orbiter. The Rosalind Franklin rover will mark Europe's first Martian surface mission, and Europe's ambitions in the field of sample return are currently being explored through potential collaborations with international partners. In a time of global uncertainty, Europe's commitment to open science and shared progress endures.



### The International Space Station: a Symbol of Peaceful Cooperation




EUROPEAN CONTRIBUTIONS TO THE INTERNATIONAL SPACE STATION

Scientific experiments on the ISS are selected through competitive peer review, ensuring only the most promising proposals are pursued. These often arise from close collaboration among partner nations, with European scientists regularly leading or playing key roles in high-impact research across a wide range of disciplines.

*Automated Transfer Vehicle*

*Columbus Laboratory*


*Cupola (ISS window)*

*General Purpose Facilities*

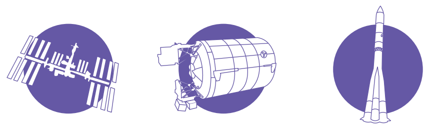
*European Robotic Arm*

*European Astronaut Corps and Research Facilities (image: Samantha Cristoforetti operating the KUBIK biological incubator)*

# 2 Physical Sciences

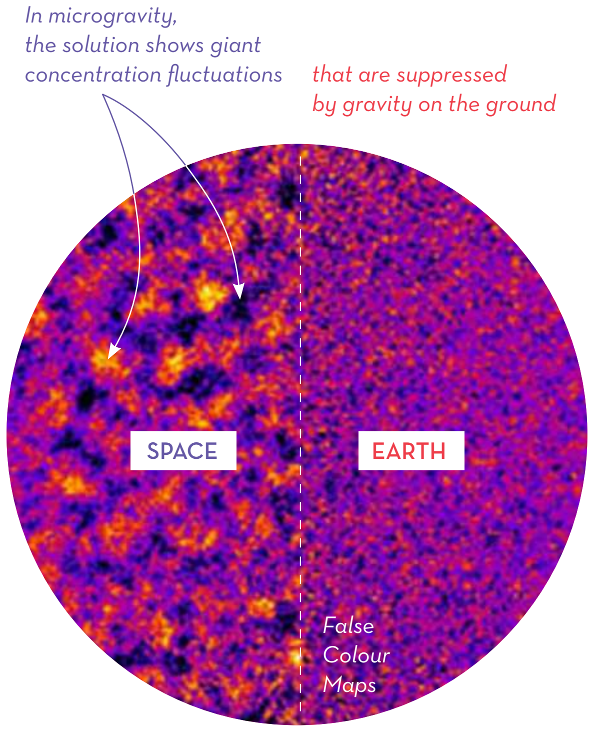
# Taming Diffusion: Pathways to Designing Novel Soft Materials

## How the microgravity environment of space helps us master the forces behind structure and form




**Diffusion is the force behind structure and form in soft materials. It shapes everything from the foams in fire safety systems, to the membranes used in clean water and medical technologies. But on Earth, gravity conceals its full behaviour. Space-based experiments provide a clearer picture, providing insights that may transform industrial processes and guide future innovation in sustainable manufacturing and space exploration.**

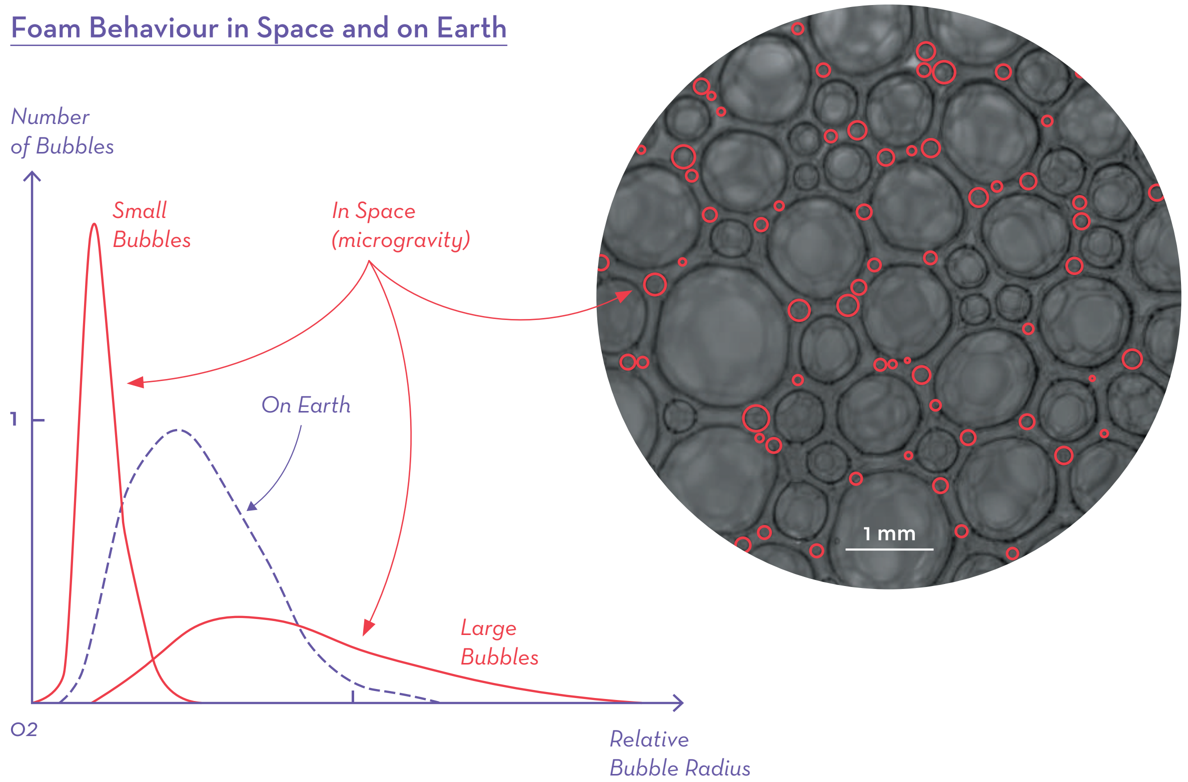
### Concentration Fluctuation in Solution in Space and on Earth




### CHALLENGE

Diffusion is one of nature's most fundamental transport processes. It drives how gases spread through foams, how particles cluster in fluids, and how materials mix at the smallest scales. But our understanding of diffusion is incomplete. On Earth, gravity competes with diffusion, masking key behaviours and skewing the structures that form. This has made it difficult to observe pure diffusion or to accurately model the growth of complex soft-matter systems (such as foams used in insulation, gels for drug delivery, or colloidal aggregates in water purification) which are central to industries from consumer products to biotechnology.

### Foam Behaviour in Space and on Earth




### DISCOVERIES

Experiments in microgravity (aboard the ISS and ESA's FOTON platform) have removed gravity from the equation, revealing how diffusion alone drives structure formation. In liquid foams, for example, diffusion alone was found to generate not only large bubbles but also a new population of small, mobile "roaming" bubbles, offering a pathway to design stronger, lightweight materials with hierarchical structure. In polymer solutions, diffusion produced giant, scale-invariant fluctuations (1,000 times larger and slower than expected), challenging conventional materials modelling. And in colloidal suspensions, the absence of convection and sedimentation led to the formation of fundamentally different particle aggregates, shaped purely by diffusion. These phenomena, previously masked or distorted by gravity on Earth, open new doors for the precise design of soft materials and advanced manufacturing processes. They also represent a step-change in our fundamental understanding of diffusion and unlock a powerful new toolkit for engineering the materials of the future.

### IMPACT

Microgravity research on diffusion is opening new doors for innovation across multiple sectors where passive transport mechanisms such as diffusion play a dominant role. In materials science, these findings inform the design of structured foams, gels, and porous media with tailored mechanical or transport properties. In biotechnology, they refine the understanding of mixing and self-assembly, relevant to drug delivery and diagnostic platforms. In space exploration, they support the development of autonomous systems for habitat construction, water recycling, and on-site resource utilisation.
As industries increasingly shift towards predictive, simulation-based material design, diffusion data from space offers a competitive edge, enabling the development of smarter, cleaner, and more resilient and sustainable products for both Earth and future space missions.

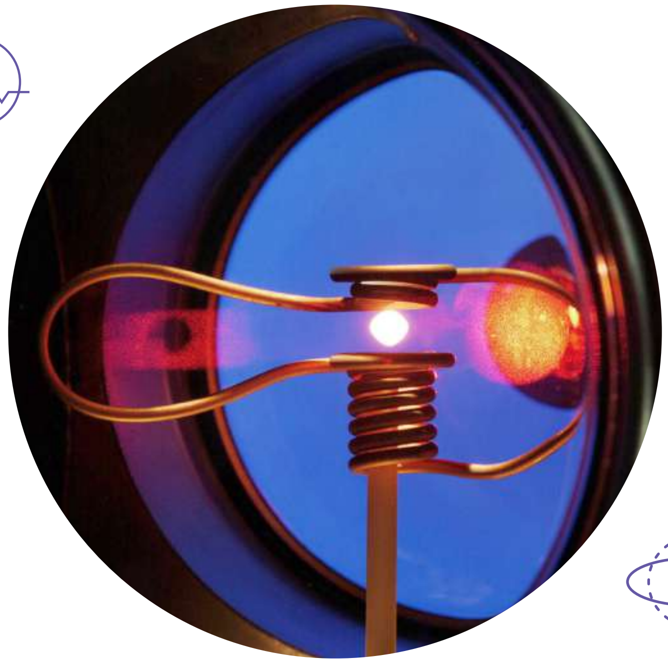
# Mastering the Melt: The Science of Liquid Metals

## Using microgravity to improve how we model, make, and master metallic materials

ISS

ELECTRO MAGNETIC LEVITATOR

Cristallisation of Alloys in Microgravity




*Metallic alloy droplet heated in the Electromagnetic Levitator (EML), allowing precise measurement of thermophysical parameters with unprecedented accuracy unobtainable on Earth.*

### CHALLENGE

In our modern world, we need metals. They support industries from energy and aerospace to electronics and medicine. The properties of these materials are shaped at the exact moment they cool and crystallise. This process determines their internal structure and, in turn, their strength, durability, and performance. Yet, despite its importance, this moment of transformation is still poorly understood. Extreme temperatures, high reactivity, and gravity make it difficult to measure key thermophysical properties (such as viscosity, surface tension, electrical conductivity, and heat capacity) during the liquid phase on Earth. These knowledge gaps constrain progress. Without precise property data, engineers must rely on estimates or trial-and-error, limiting the accuracy of simulations used in casting, welding, 3D printing, and alloy development. As industry moves towards digital design and sustainability targets, the lack of liquid-state data has become a critical bottleneck—affecting energy use, resource efficiency, and material performance across sectors.

Space experiments are essential for revealing the properties of molten metal, providing critical data that make industrial processes cleaner, smarter, and more efficient. This new knowledge benefits everything from alloy design to green manufacturing and deepens our understanding of how matter forms in the universe.

*Strongly heterogeneous nucleation at the surface associated with small undercooling*

*More homogeneous nucleation at the surface associated with large undercooling*

### DISCOVERIES

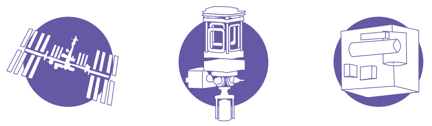
To overcome these limits, ESA developed the Electromagnetic Levitator (EML), installed on the ISS in 2014. Operating in microgravity within the Columbus module, the EML levitates molten metal droplets without a container – eliminating contamination from vessel walls. In this weightless environment, samples can be held at temperatures above 2,200 °C for over 10,000 seconds, enabling unprecedented precision in measuring their thermophysical and thermochemical properties. For the first time, researchers can study atomic structure, diffusion, and solidification in a pure, undisturbed state. ESA's ThermoLab and ThermoProp programmes have produced benchmark datasets on alloys, semiconductors, intermetallics, and glasses; data simply not achievable on Earth. These experiments also offer insights into how matter forms in space, informing theories of planetary formation and material origins.

### IMPACT

This breakthrough is changing how we make and use metals. With accurate, space-derived data, industries can shift from empirical design to predictive modelling, creating materials with enhanced properties and fewer defects. The result is a new generation of high-performance, energy-efficient products for demanding applications, from aerospace engines to medical implants. Space-based research also supports greener manufacturing. Better simulations enable more efficient use of raw materials, reduce production waste, and lower carbon emissions, helping meet environmental targets and circular economy goals.

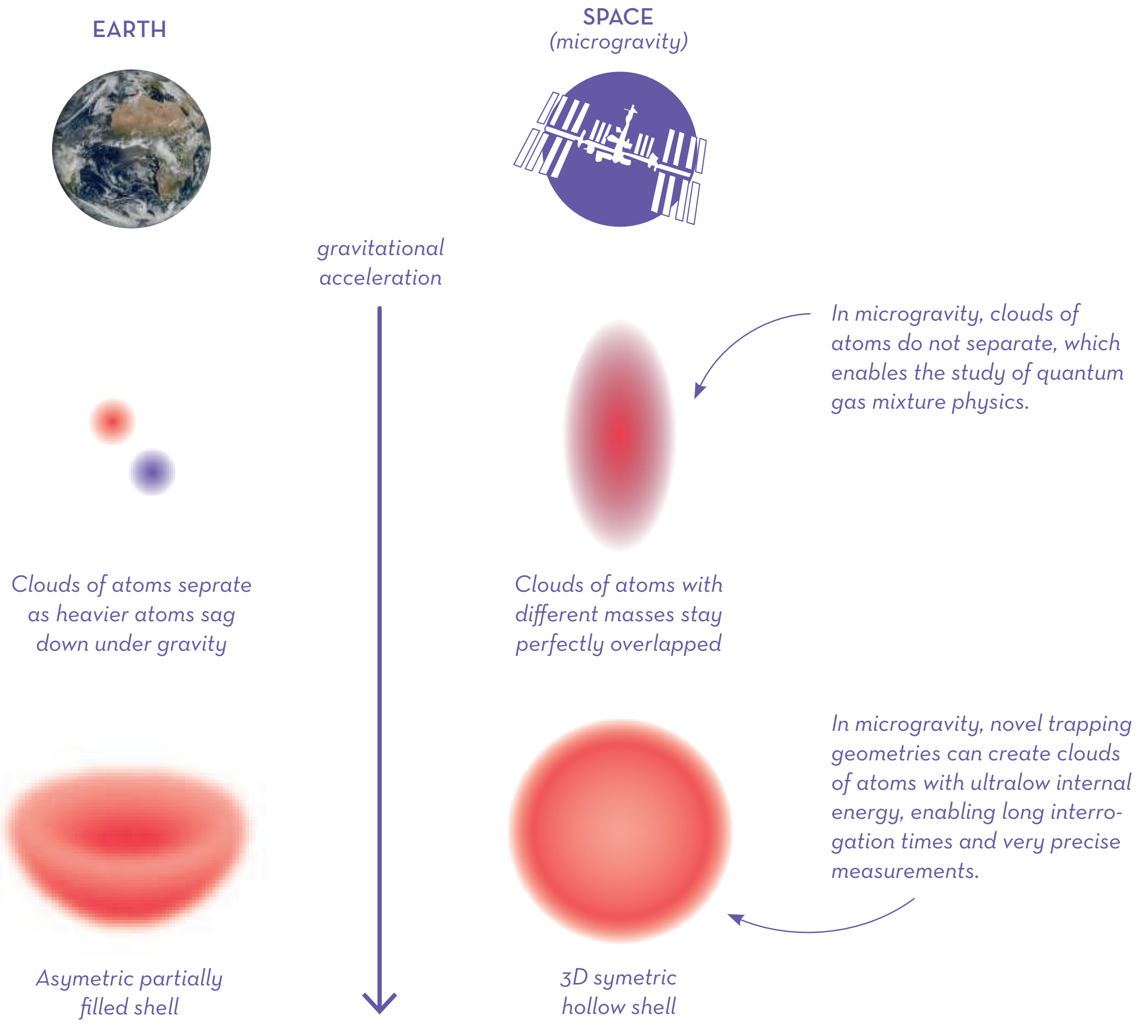
# The Cold Atom Revolution in Space

## Cold atom research in space is unveiling new insights into the laws of nature




### Microgravity Research and Applications with Ultra-Cold Atoms

*The temperature of an atomic cloud reflects how fast its atoms move, with extreme cooling bringing them close to standstill. In microgravity, such clouds can be trapped at ultralow energies without gravity pulling them apart, revealing pure mixture physics and enabling longer, more precise interferometry. On the ISS, the ACES atomic clock can observe caesium atoms for longer than on Earth, improving the sharpness of its signal; combined with its orbit, this allows levels of accuracy and gravitational tests not achievable on the ground.*




**The successful operation of cold atom systems in orbit marks a breakthrough in space-based quantum sensing, enabling precision measurement and fundamental research at an entirely new level.**


*Atomic Clock Ensemble in Space (ACES) facility attached to the Columbus module on the International Space Station.*

### CHALLENGE

Cold atom systems, especially exotic states like Bose-Einstein condensates (BECs), where atoms behave as a single quantum wave, are at the cutting edge of quantum science. They enable ultra-precise measurements of gravity, acceleration, and magnetic fields, as well as critical tests of fundamental physics. These systems are complex and delicate, typically requiring elaborate laboratory infrastructure such as high-stability lasers, precision vacuum chambers, and vibration isolation tables. As a result, their use has been limited to ground-based facilities. However, microgravity environments provide ideal conditions for cold atom experiments. In space, atoms can remain in free fall for extended durations, vastly increasing measurement sensitivity and allowing new types of quantum systems to be explored. To harness this potential, cold atom platforms must be made compact, robust, and remotely operable, all while maintaining high performance during the stresses of launch and operation in orbit.

### DISCOVERIES

With the launch of ACES (Atomic Clock Ensemble in Space), Europe has placed a space-qualified cold atom clock in orbit, opening new frontiers in precision timekeeping, global synchronisation, and fundamental physics. This mission builds on years of European-led research that has successfully validated cold atom systems for use in space. Through a sequence of missions (including parabolic flights, drop tower tests, sounding rockets, and operations on the International Space Station) BECs of rubidium and potassium have been produced, manipulated, and used for precision sensing in microgravity. These missions culminated in several world firsts: the first human-made BEC in space, the realisation of novel trapping geometries, and space-based dual-species atom interferometry. On the ISS, NASA's Cold Atom Laboratory (CAL), supported by European researchers, demonstrated the first quantum sensor in orbit capable of mapping magnetic field gradients. These achievements were made possible by major advances in system miniaturisation, control, and thermal stability, reducing expansion energies to below 50 picokelvin and enabling rugged systems to withstand launch loads of up to 50 g.

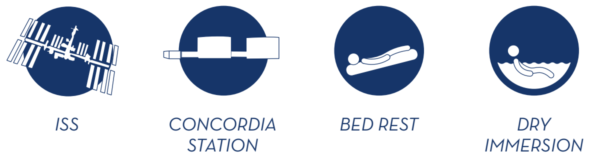
### IMPACT

The transition of cold atom technology from laboratory to orbit marks a major milestone in quantum sensing. These systems can now serve as precision instruments in future Earth observation and navigation missions, capable of detecting changes in gravity due to groundwater loss, glacial melt, or tectonic motion. Unlike conventional sensors, cold atom-based instruments operate without drift and provide absolute measurements over long timescales. Strategically, these developments support Europe's leadership in quantum technologies and secure its role in future global missions. The ACES mission features a space-qualified cold atom clock that will improve time transfer precision and enable relativistic geodesy. The upcoming BECCAL mission, jointly developed by DLR and NASA, will extend scientific reach with larger atom numbers and more sensitive interferometry. With further developments such as CARIOQA on the horizon, Europe is positioned to lead in the deployment of cold atom quantum sensors for both scientific Discoveries and operational services.

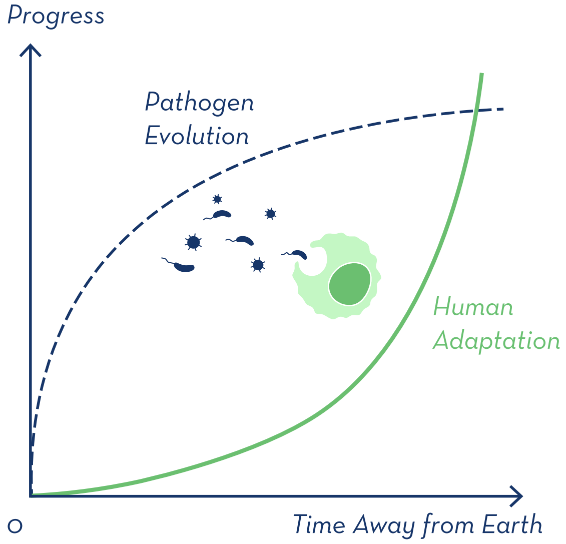
# 3 Life in Space

# The Body in Space: Systems Under Stress

## What spaceflight reveals about health, resilience, and human performance in extreme environments




**Space is a unique stress test for the human body, exposing how our systems adapt, degrade, and recover; insights that shape future missions and deliver real-world health advances on Earth.**




### CHALLENGE

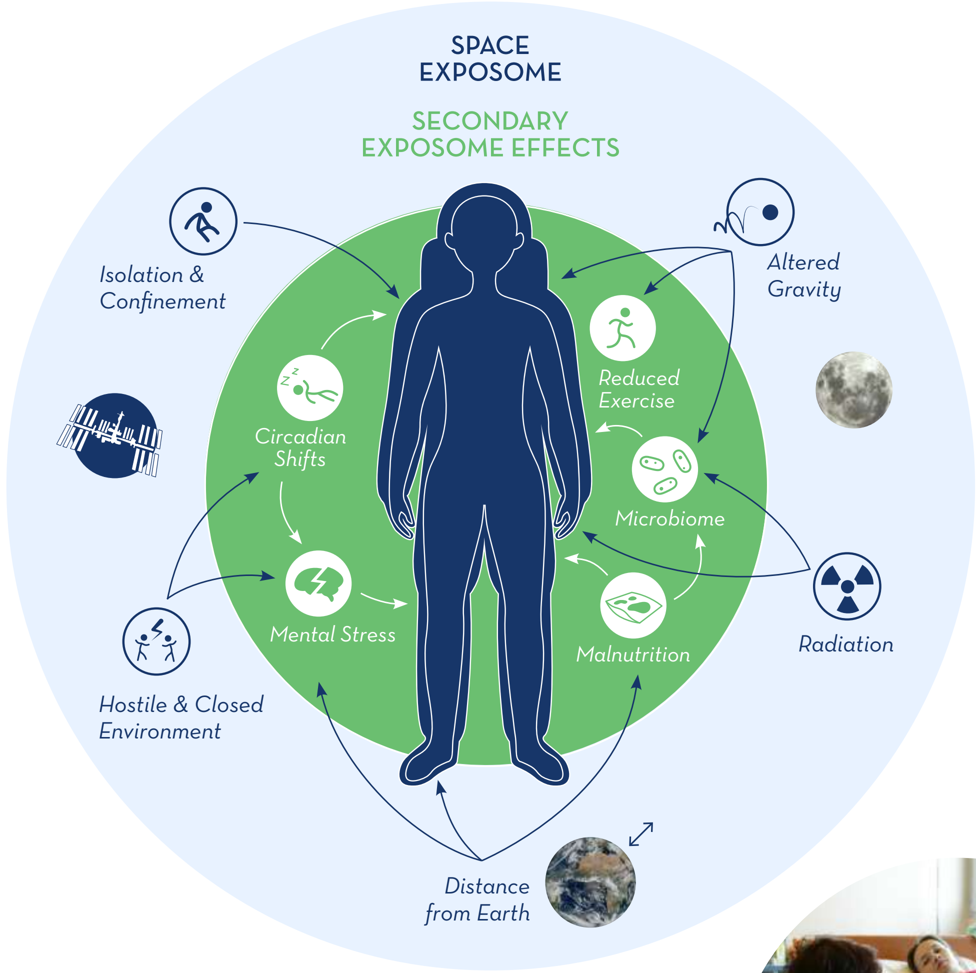
Space is an alien environment for our bodies. Without gravity, the body's finely tuned systems lose balance quickly. Muscles start wasting within days. Bone density falls rapidly, as the skeleton no longer bears weight. The cardiovascular system adapts to altered fluid distribution, leading to reduced blood volume, slower reflexes, and increased risk of fainting on return. Immune function becomes erratic, with inflammation increasing and host defence responses weakening. Vision may blur due to fluid shifts around the brain. And psychological wellbeing is taxed by confinement, isolation, altered light-dark cycles, and a lack of natural stimuli.

For space missions, these effects pose operational risks. But they also offer an unparalleled opportunity to study the human body as a complex, adaptive system under conditions that mirror certain age- or disease-related changes on Earth. Understanding these dynamics is key to sustaining life during long-duration spaceflight, and to developing more integrated approaches to health and resilience on Earth.

### DISCOVERIES

ESA has led a coordinated portfolio of life sciences research that captures the full picture of these physiological responses. Muscle research, from biopsies to advanced cell cultures in microgravity, has revealed how inactivity affects molecular pathways in metabolism, protein turnover, and mitochondrial function. Cardiac tissue flown on the ISS showed reduced contractility and signs of oxidative stress. Bedrest and dry immersion studies on Earth have replicated key elements of space deconditioning, offering high fidelity, safe, controlled models to test new interventions. Psychological studies using the French and Italian Concordia Station — a remote Antarctic outpost — have yielded insight into coping mechanisms, team cohesion, and cognitive resilience under extreme isolation. ESA's research combines these findings into integrated models of human adaptation, helping predict individual risk and tailor countermeasures.

### Environmental Factors in Space that Affect Human Health




*Bed-rest study as ground-based analog for studying of effects of Space on human health.*

### IMPACT

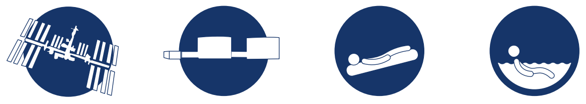
This knowledge directly informs exploration: optimised exercise protocols, personalised medical support, and health monitoring systems are all being developed for the Moon and future missions to Mars. But the benefits reach further. ESA's research supports rehabilitation strategies for patients immobilised by illness or injury, such as insights from space muscle studies now being applied to muscular dystrophy and orthopaedic recovery. Experiments like GRIP, which investigates how humans adapt their hand movements and coordination in weightlessness, offer implications for fine motor rehabilitation and assistive technologies on Earth.

Insights from ESA's research are also helping to shape rehabilitation strategies for patients immobilised by illness or injury, informs fall-prevention and fracture-reduction in ageing populations, and enhances understanding of immune decline and resilience. Research into team dynamics and psychological adaptation also feeds into civilian applications; from remote work and extreme environments to high-stress professions and long-term care settings.

# Ageing at High Speed: Space as a Model

## Using space as a fast-track model to understand, predict, and mitigate the biology of ageing




### Influence of Space on the Human Body

*ESA astronaut Pedro Duque instrumented for cardiovascular measurements.*

In microgravity, the signs of ageing unfold in weeks, offering an unprecedented window into how the body declines and how we might improve that process for people on Earth.

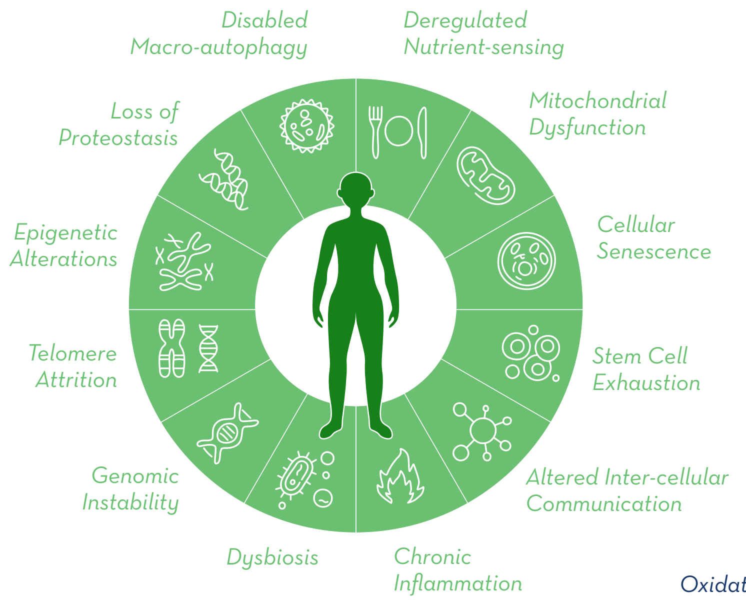
### CHALLENGE

In the words of the pioneer in stress research, Hans Selye, "every stress leaves an inedible scar, and the organism pays for its survival after a stressful situation by becoming a bit older." In short, stress makes us age – rapidly. Many of the changes astronauts experience in space are strikingly similar to those seen in older adults on Earth: loss of muscle and bone mass, weakened anti-viral immune response, cardiovascular stiffness, inflammation, sleep disturbance, and changes in cognition. But in space, these changes happen in weeks or months, not decades. This makes spaceflight a unique biological model; one that allows scientists to study ageing in accelerated, controlled conditions. As societies across Europe prepare for demographic shifts and longer life expectancies, understanding the biology of ageing has become a public health priority. The opportunity to observe, quantify, and intervene in accelerated ageing processes makes space a powerful testbed for preventative and personalised medicine.

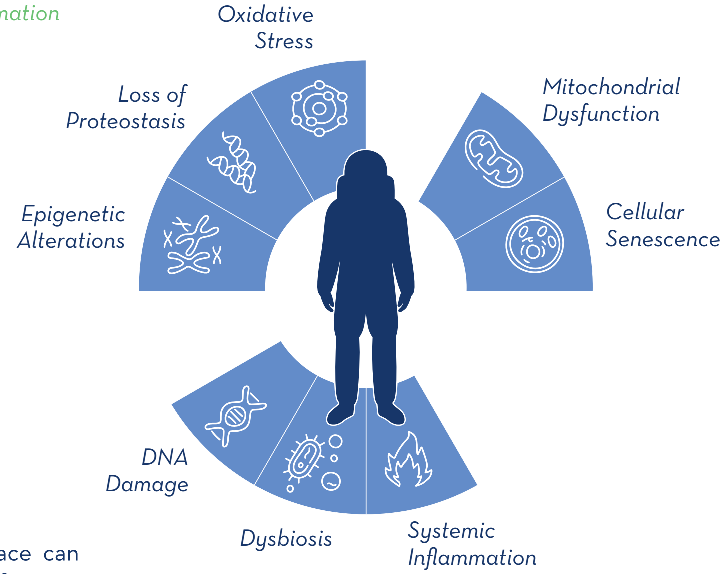




### Altered biological processes due to aging on Earth




### Altered biological processes in Space




### DISCOVERIES

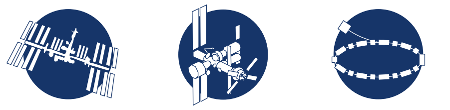
ESA-supported research has shown that space can accelerate key signs of biological ageing. Inflammation tends to increase, cells experience greater stress, and the body's energy systems become less efficient. Even the way cells record the passage of time appears to be affected. ESA research has also explored how space affects circadian rhythms, sleep quality, and brain function; key contributors to cognitive ageing. European investigators are developing and applying AI-enabled "digital twins" to model astronaut health trajectories, with potential application in predictive medicine. Novel biomarker research is defining early thresholds for physiological decline; insights that are difficult to obtain in Earth-based populations due to slower progression and higher variability. ESA is also supporting research into torpor or hibernation-like states to extend human viability during long-duration missions, a concept with future medical implications for trauma care or intensive treatment environments.

### IMPACT

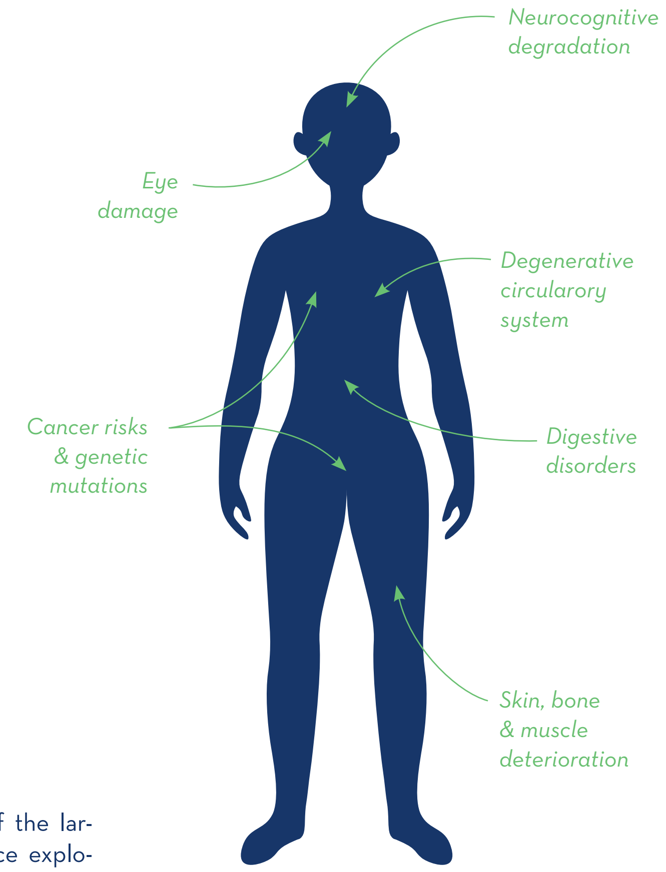
Space ageing research informs a wide range of healthcare needs. It accelerates the development of tools to detect frailty early, personalise care, and delay decline. It enhances our understanding of neurodegenerative diseases, metabolic disorders, and the immune ageing that makes older adults more vulnerable to infection and inflammation. ESA's findings are now being used to support interventions in physiotherapy, orthopaedics, geriatrics, and neurocognitive care. They also contribute to public policy discussions about active ageing, health system design, and resilience across the life course.

# Radiation and Resilience: Protecting Life Beyond Earth

## How Europe is mapping, modelling, and mitigating the greatest threat to long-duration exploration




**Radiation is one of the most difficult risks to mitigate in deep space. ESA is pioneering new tools and knowledge to protect astronauts, while advancing medicine and radiation safety on Earth.**



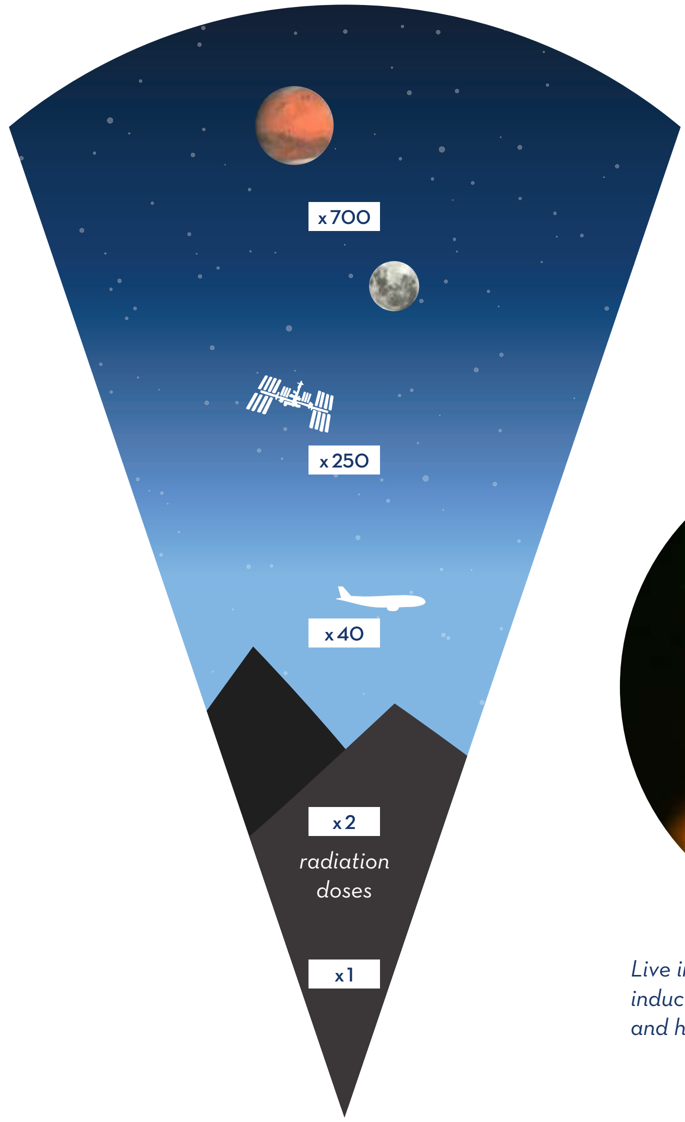

### CHALLENGE

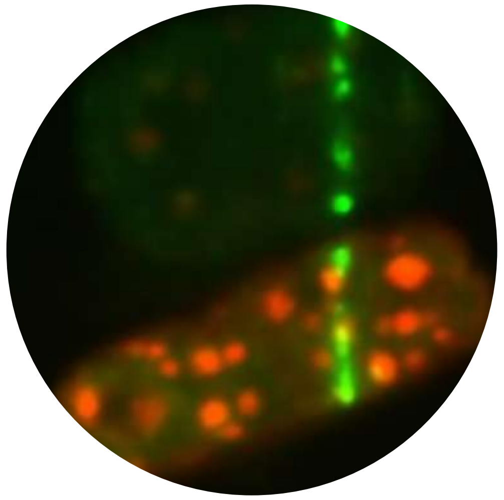
Radiation is the defining threat and one of the largest obstacles for future human deep space exploration. Unlike microgravity, which can be mitigated through exercise and environment, radiation cannot be blocked entirely. High-energy particles from solar eruptions and galactic cosmic rays penetrate spacecraft shielding and tissue, damaging DNA, increasing cancer risk, and affecting cardiovascular and neurocognitive health. For missions beyond low Earth orbit, understanding and mitigating radiation is essential, since radiation exposure will rapidly increase due to the lack of protection from the Earth's magnetic field, the increased duration of missions and the qualitatively different radiation environment in deep space.
Radiation sensitivity also differs from person to person. It varies by sex, age, genetic background and additional factors that are not fully uncovered so far. Exploring individual radiation susceptibility would open the potential for biomarker-guided interventions.

### DISCOVERIES

Europe has been a pioneer in organ-level radiation mapping. The MATROSHKA phantom, placed both inside and outside the ISS, helped establish how cosmic radiation affects different tissues during extravehicular activity, The MARE experiment, launched on NASA's Artemis I mission in 2022, sent two female phantoms (Helga and Zohar) on a flight around the Moon. Packed with over 10,000 radiation sensors, MARE generated the most detailed dataset to date on deep space radiation doses experienced by the female body. ESA is funding radiation forecasting and spacecraft exposure modelling, while developing instruments like ERSA and IDA for long-term monitoring aboard the Gateway station. Futhermore, ESA also co-funded Europe's first galactic cosmic ray simulator at GSI/FAIR in Germany, which will enable ground-based studies of space-like radiation on biological systems, tissues, organoids and organ-on-chips. This infrastructure allows scientists to test biomedical countermeasures, shielding materials, and long-term health responses under tightly controlled conditions. Several European research teams are now working on mitigation strategies, including antioxidant-based nanomedicines, precision shielding design and the radioprotective effects of hibernation. Once confined to science fiction, human hibernation is now being seriously explored by ESA as a potential option for long-duration deep space missions.

**Radiations in Space and Impacts on Health**



*Live image from a track of DNA damage (green) induced by space-like radiation in euchromatin and heterochromatin regions of a cell.*

### IMPACT

This work is enabling safer crewed missions to the Moon, Mars, and beyond. It is informing risk thresholds, mission operations, astronaut selection criteria, and vehicle design. But it is also revolutionising how we think about radiation protection on Earth. Insights into DNA repair, oxidative stress, and cellular recovery contribute to advances in cancer therapy, occupational health, and air and space travel safety. ESA's push to leverage expertise in radiation environments, shielding, dosimetry and radiobiological response is positioning Europe as a global leader in space medicine, radioprotection, and bioengineering.

# Rooted in Space: Green Habitats for the Final Frontier

## Growing food, producing oxygen, and reusing waste to sustain life beyond Earth

ISS

EUROPEAN MODULAR CULTIVATION SYSTEM

MELISSA LOOP

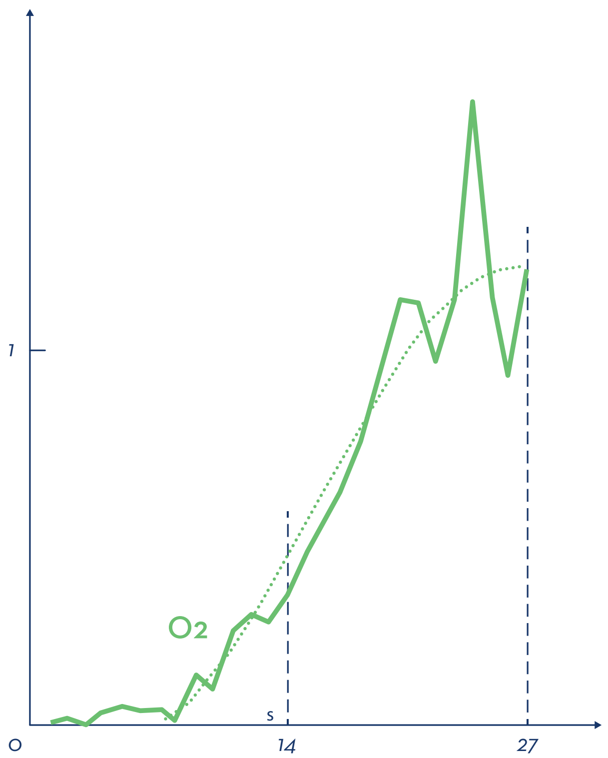
ESA's breakthroughs in using plants and algae to produce oxygen, grow food, and bacteria to recycle waste, in closed-loop systems demonstrate real-time control strategies vital for deep space missions and offer sustainable applications back on Earth.

Plants in Space to Produce Oxygen, Reycle Waste and Grow Food



### CHALLENGE

Sustaining human life during long-duration space missions requires more than launching resources from Earth. It demands the development of robust, closed-loop systems that regenerate food, oxygen, and water. Bioregenerative Life Support Systems (BLSS) address this challenge by integrating biological processes into spacecraft and habitat design. The European Space Agency (ESA) has been a pioneer in this field through its Micro-Ecological Life Support System Alternative (MELiSSA) programme, which brings together decades of research and infrastructure. Higher plants and microalgae serve as both oxygen producers and biomass generators in BLSS, and together with the bacteria they contribute to nutrient recovery. However, fine-tuning their productivity, resilience, and integration into complex life support cycles requires detailed scientific understanding under highly controlled conditions. From the physiological impact of waste recycling on plant growth to the behaviour of algae in microgravity, researchers must navigate a host of variables to make biological life support viable for space missions and applicable on Earth.




### DISCOVERIES

Ground-based experiments using the MELiSSA Plant Characterisation Unit (PCU), associated to the MELISSA Pilot Plant (MPP), have provided crucial data on plant productivity and physiology under confined environment conditions. Ground-based studies using ESA's MELiSSA Plant Characterisation Unit have quantified how crops like lettuce, kale, and Swiss chard perform under highly controlled environmental conditions, measuring their oxygen output, water use, and nutrient uptake. These experiments also showed how waste recycling methods, such as using waste-derived fertilizers with various nitrogen forms, affect plant health and productivity. On the ISS, the Arthrospira-B and Arthrospira-C experiments confirmed that microalgae can produce stable biomass and oxygen in microgravity, with light control enabling real-time oxygen regulation. Spaceflight has also shone a light on plant behaviour. For example, in microgravity, carrot roots grow toward nutrients (positive chemotropism) — a response usually masked by gravity on Earth. Gene expression studies at different gravity levels show that microgravity disrupts key signalling pathways, while Mars gravity triggers stress-adaptive responses. Together, these results advance our understanding of plant biology in space and support the development of closed-loop life support systems — knowledge equally valuable for sustainable agriculture on Earth.

### IMPACT

ESA's research demonstrates that bacteria, plants and microalgae can work together in a BLSS to deliver oxygen and biomass at levels tailored to crew needs. This paves the way for scalable, biologically integrated life support systems for human exploration of the Moon, Mars, and beyond. The ability to precisely regulate oxygen through biological means, based on crew activity and metabolic cycles, represents a significant leap towards autonomous mission operations. These findings also carry terrestrial benefits. From enhancing sustainable crop cultivation and resource recycling to supporting biofuel production and circular economy solutions, these insights contribute to ecological resilience on Earth as well as in space.crop cultivation and resource recycling to supporting biofuel production and circular economy solutions, MELiSSA's insights contribute to ecological resilience on Earth as well as in space.

# Astrobiology in Orbit: Uncovering the Limits and Origins of Life

## What ISS research reveals about life's origins and survival in extreme environments

ISS EXPOSE PLATFORM KUBIK INCUBATOR FOTON BION

ESA's long-term exposure experiments have shown that certain biomolecules and microorganisms can survive the harsh conditions of space. These findings support the search for life on other planets, strengthen planetary protection efforts, and have far-reaching implications for biotechnology, exploration, and science policy.

### CHALLENGE

Astrobiology seeks to understand the origin, evolution, and potential distribution of life beyond Earth. One of the greatest challenges in this field is replicating the extreme conditions of space in order to test how biological material and organic molecules behave beyond our planet. Laboratory simulations and terrestrial analogue environments have provided valuable insight, but they cannot fully reproduce the combined effects of vacuum, microgravity, the full solar ultraviolet spectrum, or prolonged cosmic radiation. As a result, our understanding of how life and its molecular signatures behave in space remains limited. Key questions persist: Could biomolecules or microbes survive interplanetary travel? How stable are potential biosignatures on planets like Mars? And how can we design effective life detection strategies without knowing how such compounds degrade or persist in the space environment?

### DISCOVERIES

To address this, the European Space Agency (ESA) developed a series of astrobiology exposure platforms on the International Space Station (ISS) under the EXPOSE programme. These facilities allowed over 1,500 biological and chemical samples to be directly exposed to space for extended periods, in some cases more than 500 days. The samples faced conditions such as vacuum, temperature extremes, unfiltered solar radiation, and atmospheric compositions similar to those on Mars or in interplanetary space. Some compartments included shielding to simulate different planetary environments, and all experiments were monitored with detailed environmental sensors. The findings were remarkable. Certain microorganisms (like tardigrades) and complex biomolecules not only survived but, in some cases, remained functionally intact. For example, compounds like melanin and chlorophyllin, mixed with Martian soil analogues, could still be identified using Raman spectroscopy even after long-term exposure. This provides confidence in the detection capabilities of upcoming missions, such as ESA's Rosalind Franklin rover, which will use Raman instruments to search for signs of life on Mars.



### Astrobiology on the International Space Station

*ESA Expose-R2 facility exposing biological and chemical samples to space conditions for extended periods of time.*


**ORIGINS OF LIFE**

- *Role of the terrestrial environment: specificity or generality?*
- *Role of exogenous deliveries by small bodies of the Solar System ?*
- *How chemistry spawns biology?*

**HABITABILITY AND LIMITS OF LIFE**

- *How organisms cope with extremes on Earth and beyond?*
- *Which physical extremes constrain life elsewhere?*
- *Do biological interactions increase survivability and adaptability?*
- *Can life be distributed in the Solar System?*

**SIGNS OF LIFE**

- *Extinct life: biomineralisation and fossilisation*
- *Extant life: biomolecules and biotransformation by life cycles*
- *Life detection on Earth and planetary analogues supporting future exploration*
- *Potential (exo)planetary atmosphere and surface biosignatures*

*Tardigrades are able to cope with the extreme conditions in space.*

### IMPACT

These results mark a scientific breakthrough in understanding the boundaries of life and its resilience. They offer practical guidance for designing future missions, from improving contamination controls for robotic landers to supporting the development of closed-loop life support systems for astronauts using hardy microbial species. The implications also extend beyond space. Research into the survival mechanisms of extremophiles informs biotechnology, biomedicine, and industrial microbiology, particularly in areas like DNA repair and oxidative stress. This work also challenges long-standing assumptions about the uniqueness of life on Earth and informs the ethical frameworks needed as exploration extends to Mars, icy worlds such as Europa or Enceladus, and beyond. Building on EXPOSE, ESA is now preparing the next generation of astrobiology experiments, ensuring Europe continues to lead in the search for life in the universe.

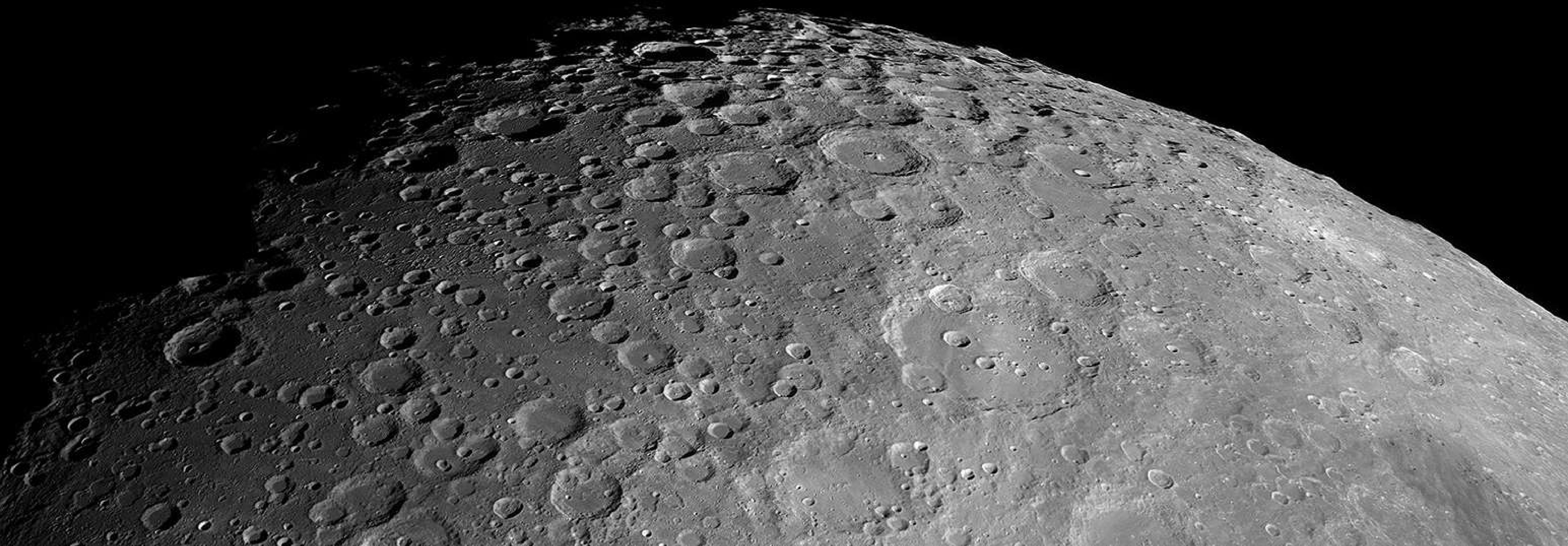
# 4 Moon

## 4.1 Lunar Resources and their Future In-Situ Use

Turning lunar icy regolith into a resource for life, fuel, and infrastructure

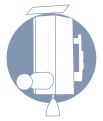
## 4.2 Lunar Environment: Surface, Dust, and Space Weather

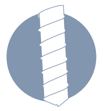
How solar wind and plasma shape airless surfaces; and why it matters



# Lunar Resources and their Future In-Situ Use

## Turning lunar icy regolith into a resource for life, fuel, and infrastructure


PROSPECT


PROSEED

Europe is developing the tools to extract water, oxygen, and materials directly from the Moon; a breakthrough that will support sustainable exploration and deliver strategic technologies for life in space and on Earth.

### CHALLENGE

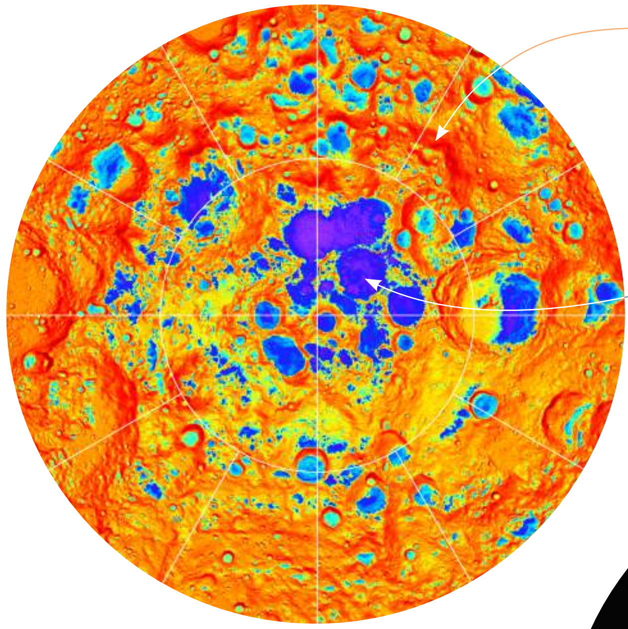
In-situ Resource Utilisation (ISRU) is the practice of producing essential resources such as water, oxygen, fuel, and building materials directly from local materials found on the Moon or other planetary bodies. By reducing reliance on supplies launched from Earth, ISRU has the potential to make lunar exploration more affordable, sustainable, and safer, paving the way for a lasting human presence beyond our planet. As such, ISRU changes the way space agencies plan missions. Water is scientifically interesting, and incredibly useful. It can be used to support life, to produce breathable oxygen, and to generate fuel by splitting it into hydrogen and oxygen. The lunar regolith, thin dust layer covering the lunar surface, is another valuable material, potentially useful for constructing infrastructure. As the world prepares to return to the Moon, identifying the availability and distribution of lunar resources, as well as developing the technological tools to transform them into consumables for autonomous or human activities are becoming a strategic priority. ESA is turning this possibility into practical reality.

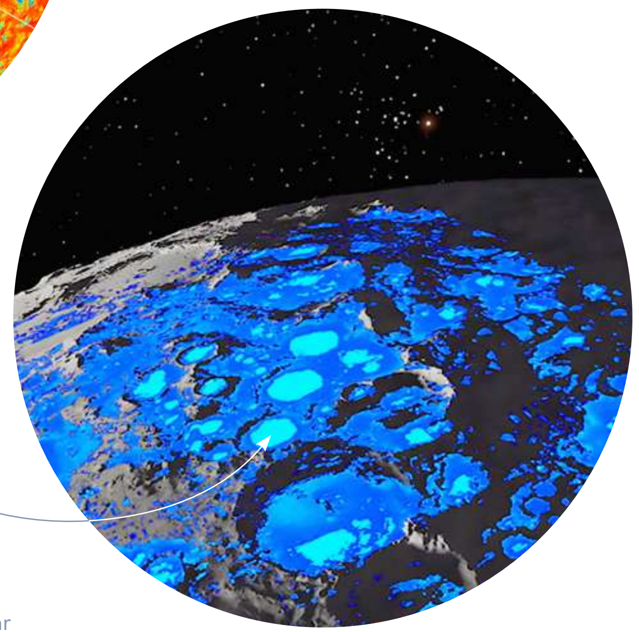
### DISCOVERIES

European scientists have played a key role in discovering the presence of water on and in the Moon. Chemical analyses of Apollo samples and lunar meteorites have been instrumental in confirming the presence of water on the Moon. Meanwhile, thermal mapping of the lunar surface and modelling its absolute age have helped identify areas where the presence of water ice is highly probable, particularly in the Permanently Shadowed Regions (PSRs) near the poles. These recent European contributions have informed the selection of landing sites in the lunar polar regions for the prospecting of water and other volatiles. This approach is transformative. Rather than carrying all supplies from Earth, astronauts could eventually live off the land; using lunar soil to produce oxygen, water, and even building materials. ESA and its partners are already testing these techniques, including using sunlight or microwaves to solidify soil into bricks and extracting oxygen from minerals such as ilmenite. These capabilities will reduce mission costs, improve sustainability, and enable longer stays on the Moon.

### Moon Water Ice Deposits

*Thermal map of the south Pole from the Diviner Lunar Radiometer Experiment aboard NASA's Lunar Reconnaissance Orbiter.*



*Potential water ice deposits around Moon south pole are reservoirs of in-situ resources to support future human exploration activities on the moon (water, oxygen, fuel)*

### IMPACT

ESA is pioneering the push toward sustainable lunar exploration by developing tools to locate and extract water and oxygen from the Moon's surface. One initiative is PROSPECT, a drill and analysis package due to fly on a future Intuitive Machines' Nova-C lunar lander, as part of NASA's Commercial Lunar Payload Services programme to the lunar south pole. PROSPECT includes a robotic drill, ProSEED, capable of collecting samples up to one metre below the surface. These can be analysed on-site by the ProSPA mini-laboratory, which will heat the material and examine its contents. The aim is to understand how much water and oxygen can realistically be extracted from the soil. The ability to extract water, oxygen, and construction materials directly from the lunar surface is revolutionary for Europe's exploration ambitions. These advances will support future ESA astronauts on the Moon, providing critical resources for habitation, mobility, and power. By developing ISRU technologies, Europe is securing a strategic role in upcoming international missions and building sovereign capabilities that will underpin long-term access to the Moon and beyond. Beyond exploration, these developments also have implications for Earth. Technologies developed to extract water, oxygen, or energy from scarce resources in space are directly relevant to sustainable mining, closed-loop resource management, and off-grid construction in remote or extreme environments on Earth. They contribute to the circular economy, reduce environmental footprint, and support technological leadership in key industrial sectors. As global interest in the Moon accelerates, Europe's contributions are turning scientific possibility into operational capability.

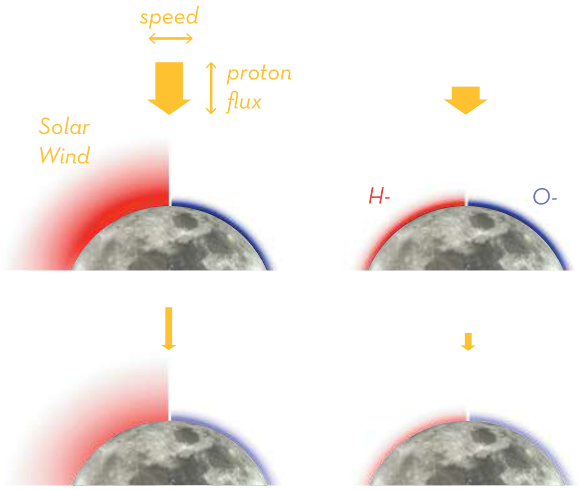
# Lunar Environment: The Surface and Space Weather

## How solar wind and plasma shape airless surfaces; and why it matters


New discoveries from the Moon show how invisible plasma interactions shape surface conditions across the solar system, with direct implications for mission design, astronaut safety, and our understanding of space weather.

### CHALLENGE

Many solar system bodies such as asteroids, planetary moons, and Kuiper Belt objects are both lacking an atmosphere and unmagnetised, leaving their surfaces directly exposed to the solar wind, ultraviolet radiation, and high-energy particles. This exposure drives processes like sputtering, solar wind implantation, and electrostatic charging, which alter surface properties and produce thin exospheres. Understanding these interactions is essential to distinguish between changes caused by internal activity, like volcanism, and those driven by space weather. The Moon, for instance, holds a long-term record of solar activity in its soil. These effects also shape the environment for future exploration, as surface charging can pose risks to equipment and astronaut safety. Studying these microscale processes, especially from the Moon, offers insights that cannot be gained on Earth or the ISS.




*Negative hydrogen (H-) and oxygen (O-) ions density on the lunar dayside measured by NILS, as a function of solar wind speed and proton flux.*

### DISCOVERIES

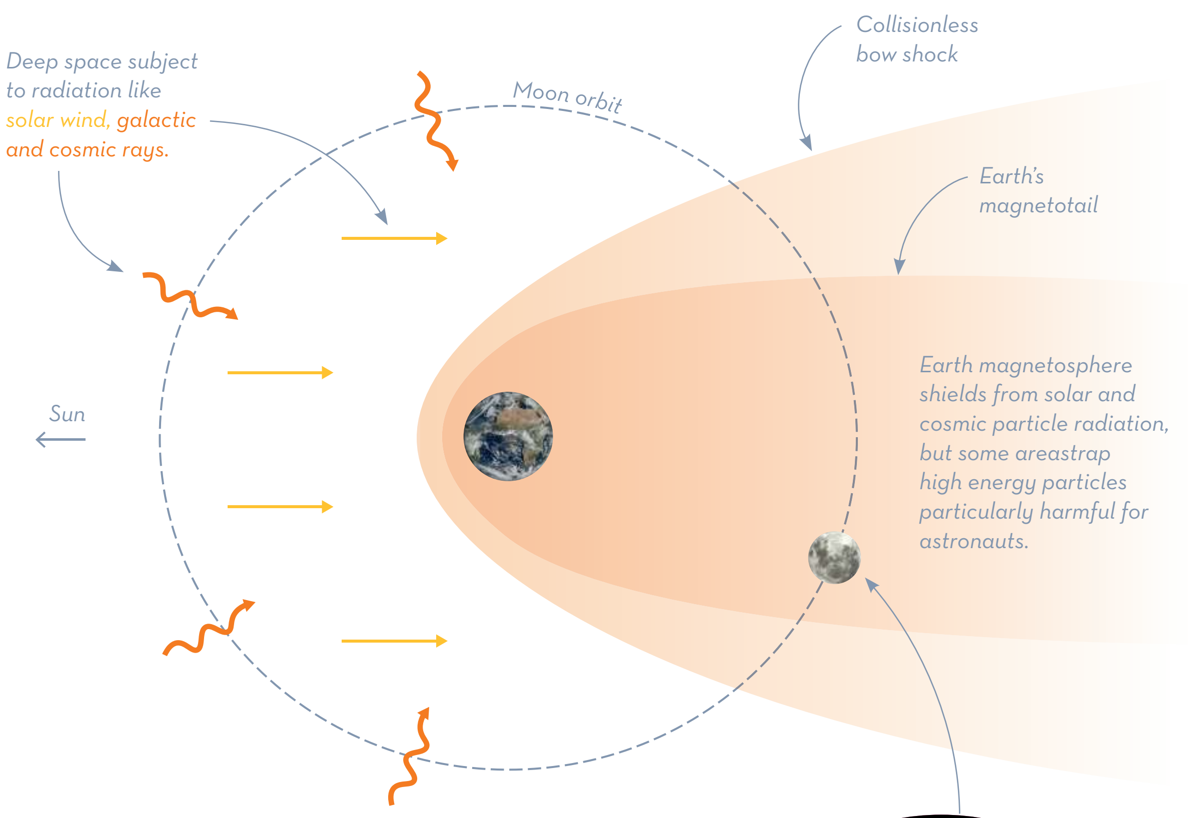
Surface charging on bodies without atmospheres occurs through a delicate balance of currents. Sunlight can cause the emission of photoelectrons, leading to positive charging, while incoming electrons from space can result in negative charging. Until recently, this was the established model, largely based on measurements from lunar missions. However, new evidence from spacecraft data and laboratory experiments has revealed more complexity. Meteoroid impacts, for example, can generate short-lived plasma clouds that disturb local electrical conditions. When the Moon passes through comet dust, its surface charges unevenly, likely due to the effects of incoming dust particles. The most significant breakthrough has come from the first direct detection of negative ions on the Moon. Recorded by the Negative Ion Lunar Spectrometer (NILS) aboard China's Chang'E 6 lander, and developed through ESA's collaboration, this marks the first time ESA has collected scientific data directly from the lunar surface. These negative ions, long predicted but never previously observed in situ, suggest a more active and varied surface–plasma environment than previously assumed.





### Lunar Environment

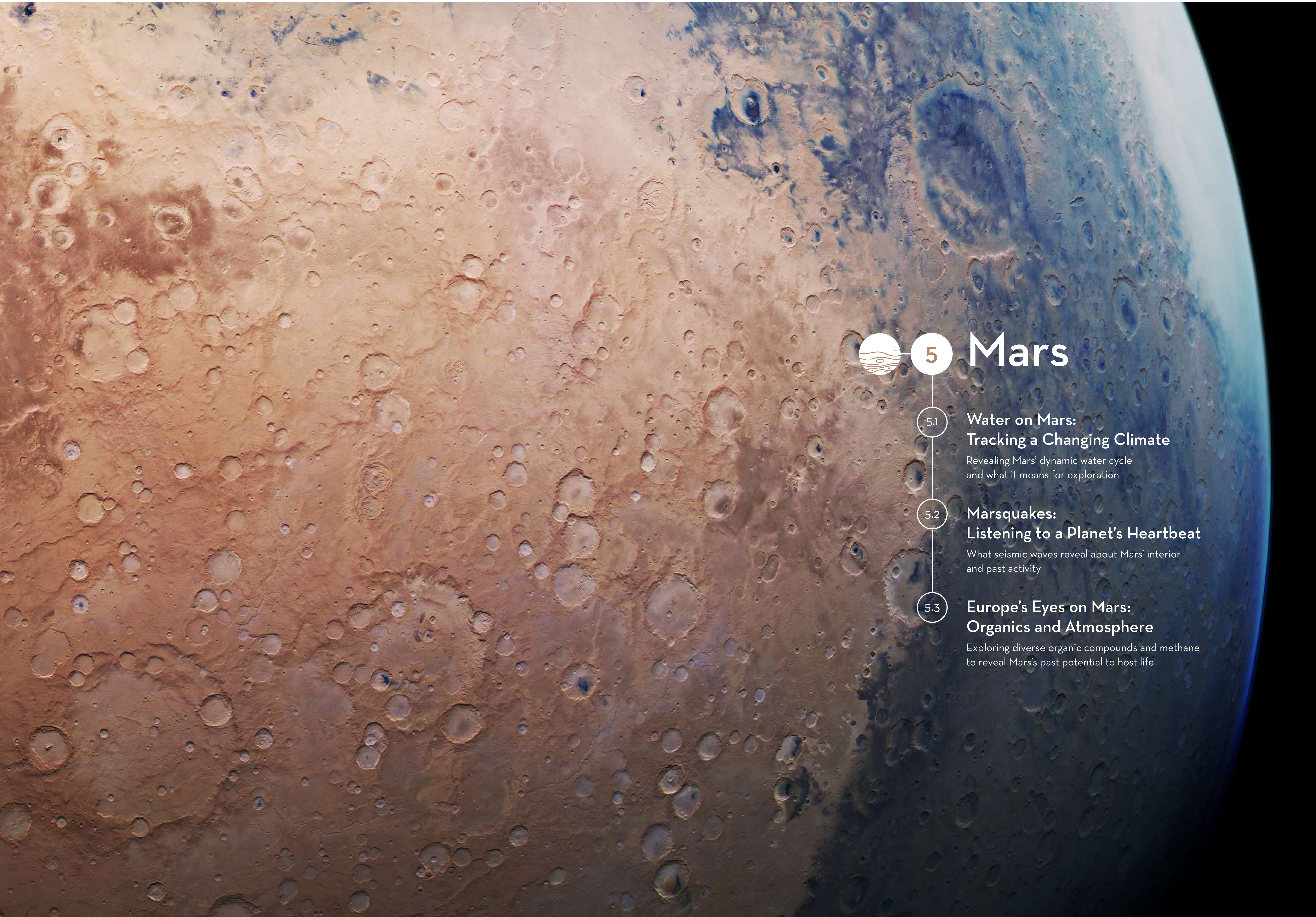
*An heliophysics instrument, on or in orbit of the Moon, can measure different radiation environments, not reproductible on Earth.*




### IMPACT

The discovery of negative ions on the Moon marks a major step in understanding how bodies without atmospheres interact with space. These ions help reveal surface properties like composition and dust behaviour, and explain how electrostatic charging can lift and move dust; posing risks to landers, instruments, and astronaut health. As Europe prepares for new lunar missions, understanding these effects is critical. ESA is developing two radiation-monitoring payloads, ESRA and IDA, to track exposure in Earth orbit and deep space. On the surface, the planned AstroLEAP instrument will support future missions by capturing real-time plasma data. These efforts will improve radiation protection, spacecraft design, and long-term crew safety, while using the Moon as a testbed for wider exploration across the solar system.

*Chang'e-6 landing site on the far side of the moon, where NILS first detected negative ions.*



# 5 Mars

## 5.1 Water on Mars: Tracking a Changing Climate

Revealing Mars' dynamic water cycle and what it means for exploration

## 5.2 Marsquakes: Listening to a Planet's Heartbeat

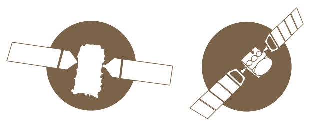
What seismic waves reveal about Mars' interior and past activity

## 5.3 Europe's Eyes on Mars: Organics and Atmosphere

Exploring diverse organic compounds and methane to reveal Mars's past potential to host life

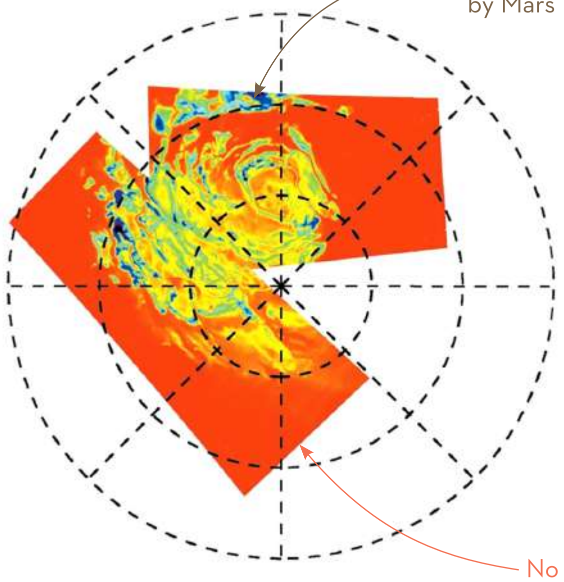
# Water on Mars: Tracking a Changing Climate

## Revealing Mars' dynamic water cycle and what it means for exploration



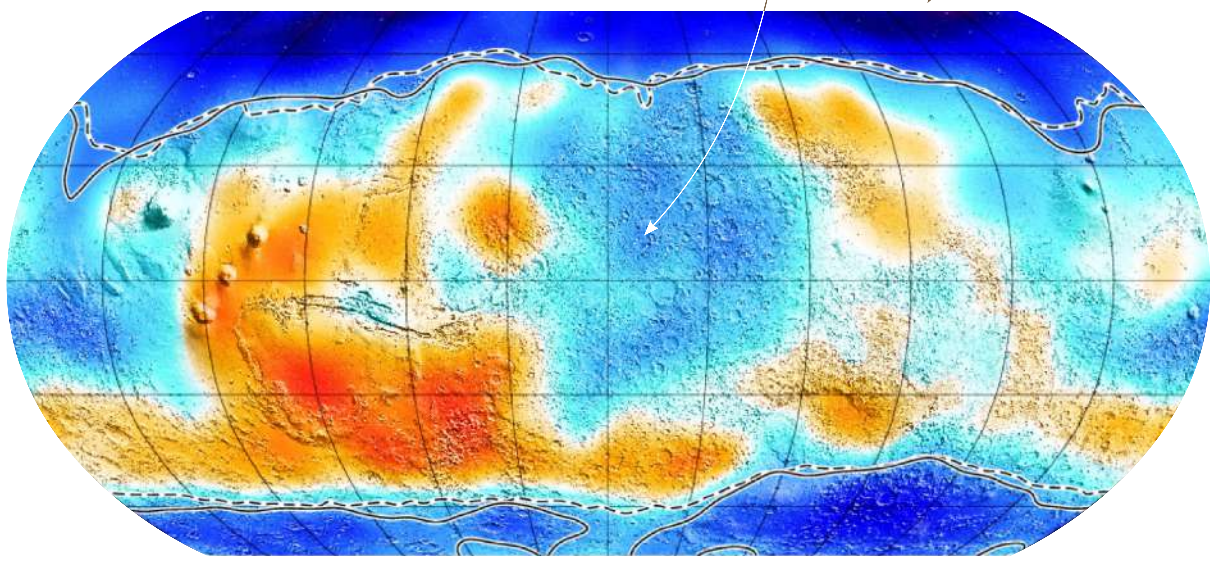

Data from Mars Express and the Trace Gas Orbiter have revealed how water moves around in space and time on Mars, information that is essential for future crewed Mars missions and for climate modelling on Earth.

### Mars Water Detections




Mars Express has discovered that water ice, not just dry ice (frozen carbon dioxide), is present year-round in Mars south polar region, stretching well beyond the polar cap into surrounding areas.

Trace Gas Orbiter has refined our understanding of wet and dry zones beneath the Martian surface and indified water rich areas near the equator, shedding new light on the planet's climate history.




### CHALLENGE

Water vapour was first detected in the Martian atmosphere from Earth in 1963, and early orbiters confirmed seasonal ice at the poles. And yet, with this discovery, many questions remained. Each northern spring, the water-rich ice cap sublimates and vapour drifts southward, but observations offered little evidence of a compensating return flow. The south polar cap appeared to consist almost entirely of carbon-dioxide ice, raising doubts about the long-term stability of the northern reservoir and leaving open questions about where Martian water is stored and how it circulates.

### DISCOVERIES

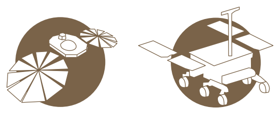
Mars Express, launched by ESA in 2003, provided the first continuous, multispectral view of the present-day water cycle. Its instruments charted water vapour, clouds, surface frost, and polar ice in unprecedented detail, revealing hidden deposits and tracking the seasonal lofting of moisture into the middle atmosphere. Follow-on measurements by the Trace Gas Orbiter extended this record, showing that water vapour can reach even higher altitudes during dust storms and that the mineral-rich regolith traps significant amounts of shallow subsurface ice. Together, the two missions demonstrated that the south polar cap also contains water ice, that dust grains act as nuclei for cloud formation, and that large-scale transport of vapour is more dynamic than earlier models predicted.

### IMPACT

These findings feed directly into global climate models for Mars and improve analogous models for Earth by clarifying how dust influences cloud microphysics. For exploration planners, mapped ice deposits and a better grasp of seasonal vapour transport identify potential resources for crewed missions and inform landing-site selection. A clearer water budget also refines assessments of past habitability and guides the search for biosignatures. By resolving decades-old questions about where Martian water resides and how it moves, Mars Express and the Trace Gas Orbiter have placed Europe at the forefront of planetary climate science while providing practical knowledge for the next phase of human and robotic exploration.

# Marsquakes: Listening to a Planet's Heartbeat

## What seismic waves reveal about Mars' interior and past activity

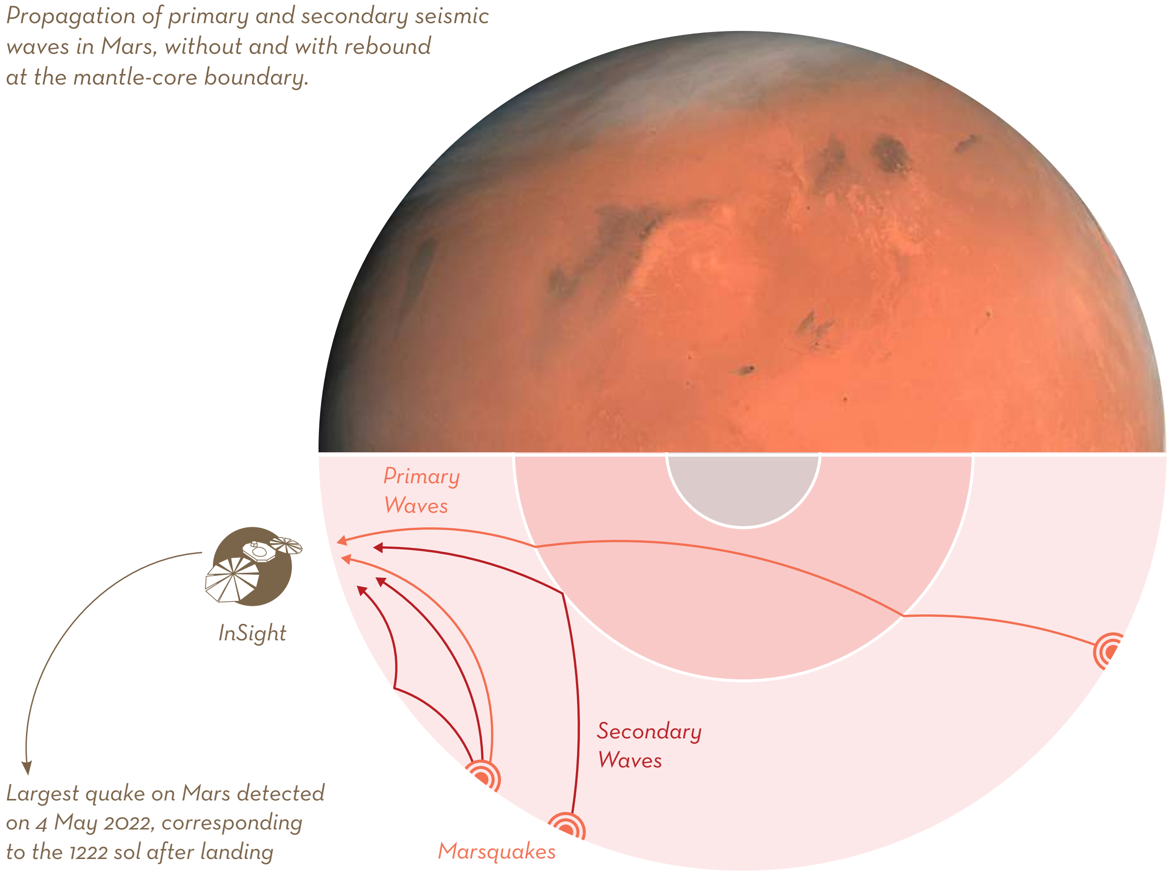


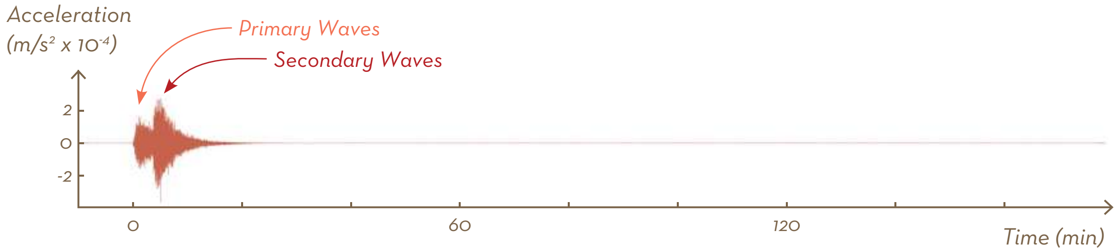
INSIGHT LANDER

EXO MARS ROVER

### Understanding Mars Interior with Quakes

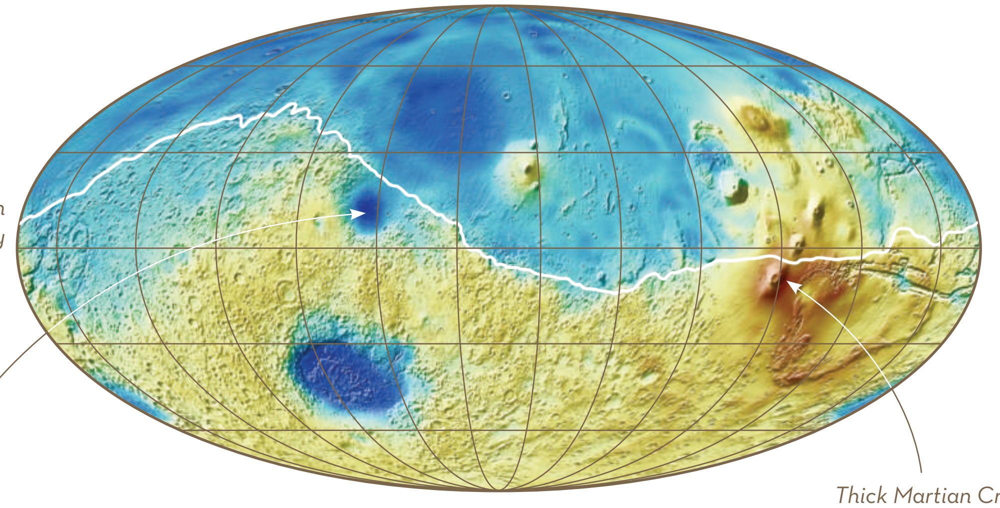
*Propagation of primary and secondary seismic waves in Mars, without and with rebound at the mantle-core boundary.*






*Global crustal thickness model derived fromseismic data collected by InSight*




### CHALLENGE

Mars has long intrigued scientists as a window into the early Solar System, but its deep interior remained a mystery. Without active plate tectonics like those on Earth, the planet appeared geologically dormant. Understanding Mars's internal structure (its crust, mantle and core) was critical for reconstructing its thermal history, assessing its volcanic past, and understanding why its geological evolution diverged from Earth's. Traditional satellite Visuals and surface observations could not penetrate below the surface, leaving these questions unanswered – until now.

### DISCOVERIES

NASA's InSight mission, which landed on Mars in November 2018, marked a turning point. At its heart was SEIS, a highly sensitive seismometer provided by CNES and developed with contributions from European institutions including IPGP, ETH Zurich, Imperial College London and DLR. On 6 April 2019, SEIS detected the first confirmed marsquake, a landmark discovery proving that Mars remains seismically active. Over the next four Earth years, SEIS recorded more than 1,300 quakes, including six caused by meteoroid impacts. The data, particularly from the largest quake on 4 May 2022, enabled researchers to analyse how seismic waves travelled through the Martian interior. This made it possible to derive the first precise internal model of the planet: a relatively thin crust (less than 72 km), a mantle extending 400–600 km, and a molten core with a radius between 1,790 and 1,870 km.

**The first detection of marsquakes has revealed that Mars is a seismically active world, with European-built instruments providing the clearest picture yet of its crust, mantle and core.**

### IMPACT

InSight's seismic measurements, made possible by European innovation and cooperation, have fundamentally advanced our understanding of Mars. The discovery that Mars remains seismically and potentially volcanically active reshapes theories about its geologic history and current state. Meteoroid-induced marsquakes also revealed ice just below the surface; an essential insight for future human missions and in-situ resource utilisation. By contributing key instruments and scientific leadership, Europe has played a decisive role in this breakthrough. These results not only transform our understanding of Mars, but also contribute to comparative planetology, offering clues about how rocky planets form and evolve across the Solar System.

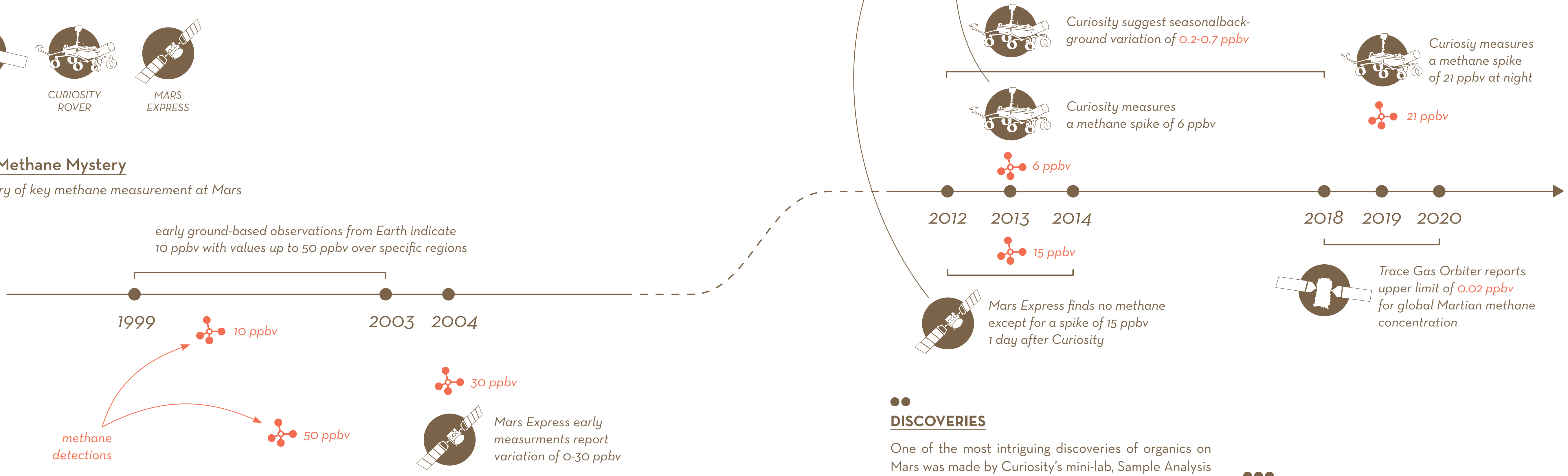
# Europe's Eyes on Mars: Organics and Atmosphere

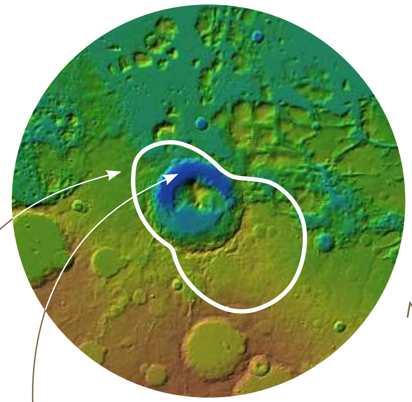
## Exploring diverse organic compounds and methane to reveal Mars's past potential to host life

TGO
CURIOSITY ROVER
MARS EXPRESS

### Mars Methane Mystery

*Summary of key methane measurement at Mars*



*Elevation map of the region surrounding Gale Crater, indicating the location of the Curiosity rover and the area where Mars Express detected a methane spike.*

**Through its orbiters and rover contributions, Europe is delivering unprecedented insights into Mars' organics and atmosphere, guiding the search for biosignatures and shaping future sample-return missions. The upcoming ESA Rosalind Franklin rover will take this quest further, bringing us closer to answering the fundamental question: was there life on Mars?**

### CHALLENGE

The detection of organic molecules on Mars is key to understanding whether life ever existed and to preparing future human missions. Such molecules can serve as potential biosignatures, but they may also stem from geological or chemical processes, including volcanism or reactions between water and rock. NASA and ESA have already confirmed the presence of ancient organics, including complex hydrocarbons, yet their origin remains uncertain. These compounds are fragile, easily destroyed by radiation, perchlorates, and ultraviolet light, and detecting them in situ demands complex drilling and sophisticated analysis. Current rovers provide valuable clues, and ESA's Rosalind Franklin rover will further expand the search, with enhanced capability to detect a wider range of organics. Yet a sample return mission, enabling more thorough analyses in terrestrial laboratories, offers the best chance to determine with confidence whether organic matter on Mars is biological or not.

### DISCOVERIES

One of the most intriguing discoveries of organics on Mars was made by Curiosity's mini-lab, Sample Analysis at Mars (SAM). After 12 years on the planet, Curiosity detected molecules with chains of up to 12 carbon atoms in a sample taken from a mudstone rich in clay, sulphates, and nitrates; an environment capable of supporting life. While SAM cannot determine in complete certainty whether these molecules are the remains of ancient life or the result of non-biological processes, their complexity hints at the potential for life-forming chemistry on Mars. Another remarkable finding concerns methane, which has sparked one of the most intense debates in Mars science. SAM, using its Tunable Laser Spectrometer, measured seasonal variations in methane levels in Gale Crater, a result partially supported by orbital detections from Mars Express. In contrast, ESA's ExoMars Trace Gas Orbiter (TGO) has reported much lower upper limits, suggesting a scarcity of the gas. Possible sources of methane include volcanism or emissions generated by microbial life. TGO, Europe's most ambitious atmospheric mission, is conducting an in-depth study using two state-of-the-art spectrometers, NOMAD and ACS. This gap between measurements fuels a rich and ongoing scientific debate.

### IMPACT

These discoveries suggest that Mars once possessed the complex chemical ingredients necessary for life, though they do not confirm that life ever existed. They build on the successes Mars Express and TGO, alongside key European contributions to NASA's Curiosity and Perseverance rovers. Future rovers, including ESA's ExoMars "Rosalind Franklin", will advance the search for more complex organic materials and offer new clues as to whether life ever arose on the Red Planet. For the very first time in Mars exploration, Rosalind Franklin's two-metre-deep drill will access samples from sheltered environments, preserving organics from radiation; a major step forward in the hunt for biosignatures. Its MOMA instrument, combining a gas chromatograph-mass spectrometer (GC-MS) with a laser desorption-mass spectrometer (LD-MS), will directly analyse complex organic compounds, including lipids and molecules up to 1,000 atomic mass units; a capability unmatched by previous missions. Discovery awaits; watch this space.

# Conclusions

Are we alone, or is there life beyond Earth? What would happen if apples do not fall downwards? Could humans survive space travel? These questions, as old as human knowledge itself, are being answered in our lifetime.

European minds have been at the forefront of extraterrestrial exploration. From the first scientific experiments on biology, physics and human physiology in space, to the extensive research possibilities on the International Space Station, Europe has been working tirelessly to advance our understanding. The original fundamental research questions have led to important technological advances (and vice-versa), with applications that are relevant both for the purpose of human space travel, as well as on Earth.

And so, the task of selecting the most emblematic European research achievements of the past two decades was not simple. The examples featured in this brochure represent only a glimpse of the breadth and depth of scientific research enabled by the Human and Robotic Exploration programme. While care was taken to reflect a diverse and representative selection, many important contributions could not be included; a testament to the richness of the field and the strength of Europe's research community.

Thanks to the combined effort of many scientists across the ESA member states, we have deepened our understanding of the role of gravity in biological processes from the cellular level to bacteria, plants and animals including ourselves. At the same time, we learned about the amazing flexibility of life to adapt to a wide range of external circumstances, enhancing our understanding of the possibilities for extraterrestrial life, but also how humans can survive long-duration spaceflight. Many of these findings also help understand biological processes on Earth and have direct relevance for health, in particular age-related health problems.

In the physical sciences domain, experiments in the absence of gravity-driven phenomena like convection allowed the detailed study and theoretical understanding of properties and behaviour of matter in the fluid state, ranging from pure liquids to foams, emulsions and molten metals, deepening our understanding of processes like boiling, solidification, and combustion. This expertise not only advances industrial applications on Earth but also supports future exploration by informing resource use and manufacturing in space.

European scientists together with their international partners have also brought major contributions in the understanding of our direct neighbours; the Moon and Mars. In particular, the presence of water and the possibility of harbouring past or present lifeforms are of key interest. Using remote observations and in collaboration with other space agencies, a better understanding of planetary geophysics, water reservoirs and transport as well as organic processes has emerged. Thus, we are prepared for the next decade, when ESA's own research infrastructure on Moon and Mars will gradually become available.

The merging of the robotic and human aspects of exploration allows for an optimal way to combine the collected knowledge of the past to address the upcoming scientific and technological challenges of the future. In a rapidly changing world, Europe has the chance to turn its legacy of excellence into lasting leadership, securing its place at the heart of humanity's next great journey beyond Earth.

Marc Heppener
Vice-Chair, European Space Sciences Committee

# References

## 1 Cooperation

### 1.1 European Infrastructure, Global Impact: The ISS and Beyond

IMAGE CREDITS

© NASA/ESA-T. Pesquet

## 2 Physical Sciences

### 2.1 Taming Diffusion: Pathways to Designing Novel Soft Materials

IMAGE CREDITS

Bubble size images and graphics adapted from Galvani et al., 2023 (with approval from the authors), concentration map © ESA.

BIBLIOGRAPHY


**Galvani et al., 2023.** *Hierarchical bubble size distributions in coarsening wet liquid foams.*

**Veen et al., 2012.** *Colloidal aggregation in microgravity by critical Casimir forces.*

**Vailati et al., 2011.** *Fractal fronts of diffusion in microgravity.*


### 2.2 Mastering the Melt: The Science of Liquid Metals

IMAGE CREDIT

EML image © DLR, nucleation images adapted from Luo et al., 2020.

REFERENCES


**Novakovic et al., 2024.** *Viscosity of liquid Ni-based industrial alloys: experiments versus theory.*

**Fecht & Mohr, 2022.** *Metallurgy in Space.*

**Herlach et al., 2006.** *Report of the Non-Equilibrium Solidification Project.*

**Matson et al., 2023.** *Electromagnetic levitation containerless processing of metallic materials in microgravity: rapid solidification.*

**Luo et al., 2020.** *Thermophysical properties of a Si50Ge50 melt measured on board the International Space Station.*


### 2.3 The Cold Atom Revolution in Space

IMAGE CREDIT

Graphics adapted from Frye et al., 2021, rendering of ACES and the Columbus module © ESA-D. Ducros.

REFERENCES


**Barrett et al., 2016.** *Dual matter-wave inertial sensors in weightlessness.*

**Becker et al., 2018.** *Space-borne Bose-Einstein condensation for precision interferometry.*

**Cacciapuoti et al., 2020.** *Testing gravity with cold-atom clocks in space: The ACES mission.*

**Frye et al., 2021.** *The Bose-Einstein Condensate and Cold Atom Laboratory.*

**Williams et al., 2024.** *Pathfinder experiments with atom interferometry in the Cold Atom Lab onboard the International Space Station.*


## 3 Life in Space

### 3.1 The Body in Space: Systems Under Stress

IMAGE CREDIT

Image © CNES-S. Levin, 2005, infographic adapted from Marchal et al., 2024.

REFERENCES


**Marchal et al., 2024.** *Challenges for the human immune system after leaving Earth.*

**Hughson et al., 2018.** *Heart in space: effect of the extraterrestrial environment on the cardiovascular system.*

**Seidler et al., 2024.** *Effects of spaceflight on the brain.*

**Liphardt et al., 2023.** *Musculoskeletal research in human space flight – unmet needs for the success of crewed deep space exploration.*

**Choukèr, 2020.** *Stress Challenges and Immunity in Space.*


### 3.2 Ageing at High Speed: Space as a Model

IMAGE CREDIT

Image © ESA-P. Duque, infographic adapted from Malhan et al., 2023.

REFERENCES


**Strollo and Vernikos, 2021.** *Aging-like metabolic and adrenal changes in microgravity: State of the art in preparation for Mars.*

**Mairesse et al., 2019.** *Preparing for Mars: human sleep and performance during a 13 month stay in Antarctica.*

**Malhan et al., 2023.** *Circadian regulation in aging: Implications for spaceflight and life on earth.*


### 3.3 Radiation and Resilience: Protecting Life Beyond Earth

IMAGE CREDIT

Infographic © ESA and image provided by B. Jakob (data from Jakob et al., 2011).

REFERENCES


**Chancellor et al., 2014.** *Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit.*

**George et al., 2024.** *Space radiation measurements during the Artemis I lunar mission.*

**Schuy et al., 2020.** *Hybrid Active-Passive Space Radiation Simulation Concept for GSI and the Future FAIR Facility.*

**Cerri et al., 2016.** *Hibernation for space travel: Impact on radioprotection.*

**Jakob et al., 2011.** *DNA double-strand breaks in heterochromatin elicit fast repair protein recruitment, histone H2AX phosphorylation and relocation to euchromatin.*


### 3.4 Rooted in Space: Green Habitats for the Final Frontier

IMAGE CREDIT

Image and graphic adapted from Schiefloe et al., 2023.

REFERENCES:


**Pannico et al., 2022.** *A Plant Characterization Unit for Closed Life Support: Hardware and Control Design for Atmospheric Systems Front.*

**Schiefloe et al., 2023.** *From urine to food and oxygen: effects of high and low NH4+:NO3- ratio on lettuce cultivated in a gas-tight hydroponic facility.*

**Poughon et al., 2020.** *Limnospira indica PCC8005 growth in photobioreactor: model and simulation of the ISS and ground experiments.*

**Izzo et al., 2019.** *Chemotropic vs Hydrotropic Stimuli for Root Growth Orientation in Microgravity.*

**Medina et al., 2022.** *Red Light Enhances Plant Adaptation to Spaceflight and Mars g-Levels.*

# References


### 3.5 Astrobiology in Orbit: Uncovering the Limits and Origins of Life

IMAGE CREDIT

Expose-R2 image © ROSCOSMOS, tardigrade image provided by Adam Mickiewicz University (Milena Roszkowska, Magdalena Gawlak, Łukasz Kaczmarek and Andonis Karachitos), text adapted from ESA SciSpacE white Paper #10: Astrobiology.

REFERENCES

**Elsaesser et al., 2023.** *Future space experiment platforms for astrobiology and astrochemistry research.*

**Rabbow et al., 2017.** *EXPOSE-R2: The Astrobiological ESA Mission on Board of the International Space Station.*

**de Vera, 2019.** *Special Collection: BIOMEX (BIOlogy and Mars EXperiment).*

**Baqué et al., 2022.** *Biosignature stability in space enables their use for life detection on Mars.*

**Carrasco et al., 2015.** *The AMINO experiment: methane photolysis under Solar VUV irradiation on the EXPOSE-R facility of the International Space Station.*

## 4 Moon

### 4.1 Lunar Resources and their Future In-Situ Use

IMAGE CREDIT

Image © ESA (based on data from Paige et al., 2010) and thermal map adapted from the NASA PDS/Diviner Archives (reference: Williams et al., 2019).

REFERENCES

**Anand, 2010.** *Lunar water: a brief overview.*

**Brown et al., 2022.** *Resource potential of lunar permanently shadowed regions.*

**Lomax et al., 2020.** *Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith.*

**Sargeant et al., 2020.** *Feasibility studies for hydrogen reduction of ilmenite in a static system for use as an ISRU demonstration on the lunar surface.*

**Williams et al., 2019.** *Seasonal polar temperatures on the Moon.*

### 4.2 Lunar Environment: Surface, Dust, and Space Weather

IMAGE CREDIT

Image © CNSA/CLEP, lunar environment infographic adapted from Dandouras et al., 2023, NILS negative detection infographic adapted from Wieser et al., 2025.

REFERENCES

**Canu-Blot et al., 2025.** *The Negative Ions at the Lunar Surface (NILS) Instrument on the Chang'E-6 Mission.*

**Dandouras et al., 2023.** *Space plasma physics science opportunities for the lunar orbital platform – Gateway.*

**Reiz et al., 2012.** *Radiation exposure in the Moon environment.*

**Wieser et al., 2025.** *Direct observations of negative ions on the lunar surface by Chang'E-6.*

## 5 Mars

### 5.1 Water on Mars: Tracking a Changing Climate

IMAGE CREDIT

Image of the south pole of Mars © ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO, Mars Express water detection map adapted from Bibring et al., 2024, TGO subsurface water distribution © ESA (data from Mitrofanov et al., 2018).

REFERENCES

**Montmessin et al., 2024.** *Mars' water cycle and escape: a view from Mars Express and beyond.*

**Bibring et al., 2004.** *Perennial water ice identified in the south polar cap of Mars.*

**Mitrofanov et al., 2022.** *The evidence for unusually high hydrogen abundances in the central part of Valles Marineris on Mars.*

### 5.2 Marsquake: Listening to a Planet's Heartbeat

IMAGE CREDIT

Image © ESA & MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA, diagram adapted from Stähler et al., 2023, seismic graphics provided by P. Lognonné and crustal thickness model adapted from Wieczorek et al., 2022 (with approval from the authors).

REFERENCES

**Lognonné et al., 2023.** *Mars seismology.*

**Wieczorek et al., 2022.** *InSight constraints on the global character of the Martian crust.*

**Stähler et al., 2023.** *Seismic detection of the martian core.*

**Andrews-Hanna, 2022.** *Marsquakes coming into focus.*

### 5.3 Europe's Eyes on Mars: Organics and Atmosphere

IMAGE CREDIT

Infographic adapted from © ESA, elevation map from USGS/Fergason et al., 2018 using a combination of ESA/MEX/HRSC and NASA/MGS/MOLA data and location of the Mars Express methane measurement from ESA/Giuranna et al. (2019).

REFERENCES

**Korablev et al., 2019.** *No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations.*

**Giuranna et al., 2019.** *Independent confirmation of a methane spike on Mars and a source region east of Gale Crater.*

**Vandaele et al., 2023.** *Composition and Chemistry of the Martian Atmosphere as Observed by Mars Express and ExoMars Trace Gas Orbiter.*

**Freissinet et al., 2025.** *Long-chain alkanes preserved in a Martian mudstone.*

**Vago et al., 2017.** *Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover.*

# Imprint

This document was commissioned by the European Space Agency to the European Science Foundation and the European Space Sciences Committee (PO N. 5001041653).

AUTHORS

**European Space Sciences Committee**

Life and Physical Sciences Panel: Charlot Vandevoorde (Panel Chair), Kai Bongs, Roberto Cerbino, Alexander Choukér, Luca Cipelletti, Denise Ferravante, Asuncion Garcia- Escorial, Marc Heppener, Ann-Iren Kittang Jost, Nicola Montano, Ruth-Sophie Taubner

Solar System Exploration Panel: Nicole Schmitz (Panel Chair), Vinciane Debaille, Sonia Fornasier, Mauro Messerotti, Christina Plainaki, Michel Viso

Chris Rapley (ESSC Chair)

**External Contributors**
Mahesh Anand, Hans Fecht, Dominique Langevin, Christophe Lasseur, Matthias Meister, Antonia Neels, Albert Roura

**European Science Foundation**
Jonas L'Haridon, Courtney Allison, Alice Stephant

EDITORS

**European Science Foundation**
Jonas L'Haridon, Courtney Allison

DESIGN

**Artistic Direction / Graphic Design**
Carine Baudet

**Graphic Design**
Guillemette Crozet
Jonas L'Haridon

PUBLICATION DATE

10 September 2025

doi: 10.5281/zenodo.15856015