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Opinion/Position paper

Goals and trends in space exploration: An overview of the panel on exploration sessions at the committee on space research general assembly 2024

André Galli [1],*, Heather Smith [2], Michel Blanc [3], Bernard Foing [4,5,6,7,8,9,10,11], Hélène Boithias [12], Scott J. Bolton [13], Soyoung Chung [14], Athena Coustenis [15], Eric Dautriat [16], Jean-Pierre de Vera [17], Peter Doran [18], François Dubrulle [19], Fatemeh Fazel Hesar [20], Carolin Frueh [21], Shaifali Garg [22], Niklas Hedman [23], Kyeong J. Kim [24], Stéphanie Lizy-Destrez [25], Andreas Losch [26,27], Alessandra Marino [28], Christopher McKay [36], Patrick Michel [29,30], Olivier Mousis [31], Antonino Salmeri [32], Udit Shah [33], Shine S. R. [34], Michael Sims [33], Jean-Claude Worms [23], Hajime Yano [35]

[1] Space Research & Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland
[2] KIPR/NASA Ames Research Center, Moffett Field, CA, USA
[3] Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
[4] Leiden Observatory, Leiden, The Netherlands
[5] Space Renaissance International, Viale Risorgimento, 57, 22073 Fino Mornasco (CO), Italy
[6] ILEWG LUNEX EuroSpaceHub EuroMoonMars, France
[7] ERA Space Photonics Chair Riga University, Latvia
[8] Nanjing NUAA & Beijing Institute of Technology, China
[9] Hong Kong U LSR Laboratory for Space Research, Hong Kong Special Administrative Region of China
[10] QOSMOSYS, Singapore
[11] formerly ESA ESTEC, The Netherlands
[12] Airbus Defence and Space, Toulouse, France
[13] Southwest Research Institute & University of Texas, San Antonio, USA
[14] Korea Aerospace Research Institute, Republic of Korea
[15] LIRA, Paris Observatory, Univ. PSL, Sorbonne Univ., Université Paris Cité, CY Cergy Paris Univ., CNRS, Meudon, France
[16] Air and Space Academy, Toulouse, France
[17] German Aerospace Center (DLR), Space Operations and Astronaut Training, Microgravity User Support Center (MUSC), Cologne, Germany
[18] Department of Geology and Geophysics, Louisiana State University, Baton Rouge, USA
[19] Qosmosys, Singapore, Singapore
[20] Leiden Institute of Advanced Computer Science, Leiden, The Netherlands
[21] Purdue University, West Lafayette, USA
[22] Geoinformation Science Department, The Indian Institute of Remote Sensing, Dehradun, India
[23] Committee on Space Research c/o CNES, Paris, France
[24] Korea Institute of Geoscience and Mineral Resource, Daejeon, Republic of Korea
[25] DCAS/Space Advanced Concepts Laboratory, Toulouse, France
[26] University of Bern, Bern, Switzerland
[27] University of Zurich, Zurich, Switzerland
[28] The Open University, Milton Keynes, UK
[29] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange Laboratory, Nice, France
[30] The University of Tokyo, Department of Systems Innovation, School of Engineering, Tokyo, Japan
[31] Solar System Science and Exploration Division, Southwest Research Institute, Boulder, CO, USA
[32] Lunar Policy Platform, Tallinn, Estonia
[33] Ceres Robotics, Oakland, CA, USA
[34] Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Thiruvananthapuram, India
[35] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan
[36] NASA Ames Research Center, Moffett Field, CA, USA

* Corresponding author.
E-mail address: andre.galli@unibe.ch (A. Galli).

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ABSTRACT

In response to the growing importance of space exploration, the objectives of the COSPAR Panel on Exploration (PEX) are to provide high quality, independent science input to support the development of a global space exploration program, to promote space sciences as a key element of this program, to contribute to maximize its scientific return via enhanced international cooperation, and to take action to safeguard the scientific assets of solar system bodies. This paper summarizes the presentations of the two panel sessions at the COSPAR assembly 2024 and identifies the most intensely discussed recent topics of interest or concern for space exploration. These topics include environment stewardship of celestial bodies, space debris, resource utilization, the Moon, Mars, and other celestial bodies that we want to explore with planetary protection measures, preservation of dark and quiet skies, potential atmospheric pollution, space as an independent goal of sustainable development, human spaceflight, agile and affordable space programs, and the early preparation of a new edition of the COSPAR exploration roadmap.

1. Introduction

The Committee on Space Research (COSPAR) has originated in the beginnings of the space age. It was established at the International Council of Scientific Unions (nowadays the International Science Council) during an international meeting in 1958. The purpose of COSPAR, by its Charter from the International Science Council, is “to promote at an international level scientific research in space, with emphasis on the exchange of results, information and opinions, and to provide a forum, open to all scientists, for the discussion of problems that may affect scientific space research”. The objectives of COSPAR are achieved through the organization of scientific assemblies, publications, and other means.[1]

COSPAR has 8 scientific Commissions and 12 Panels. Among them, the Panel on Exploration[2] was initiated in 2012 to provide independent scientific advice to support space exploration in general, to safeguard the present and potential scientific value of solar system objects, and to understand the consequences of ongoing and planned research, exploration, and utilization activities. This advice is drawn from the expertise provided via the contacts maintained by COSPAR’s various bodies with the international community and scientific entities. This setup is to ensure a consensus view of the international scientific community on the guidance for a long-term sustainable space exploration with international cooperative efforts.

PEX builds on activities of working groups reporting to COSPAR such as the International Mars Exploration Working Group[3] and the International Lunar Exploration Working Group,[4] various COSPAR commission and panels as well as partner organizations such as the International Academy of Astronautics (Huntress et al., 2006), and the International Space Exploration Coordination Group (ISECG, 2024).

PEX is providing its advice and analyses to the COSPAR Bureau and Council, as well as to concerned governmental and space agencies, private entities, and the public. As part of this task, PEX organizes scientific sessions at each COSPAR assembly to discuss recent developments and showcase new achievements in science, technology and other fields relevant to space exploration. This paper provides a brief overview of the studies and activities presented at the PEX sessions of the COSPAR Scientific Assembly 2024 in Busan, South Korea (Section 2), and gives an overview of the currently most intensely discussed topics of interest for space exploration and the current task of PEX to define a new space exploration roadmap (Section 3).

2. Summary of the contributions at the PEX session of the COSPAR Scientific Assembly 2024

In this section we provide an overview of all presentations of the PEX1 and PEX2 sessions at the COSPAR Scientific Assembly 2024. The presentations in this paper follow the sequence: ethical considerations, implications for current exploration and resource utilization, and future missions and space exploration concepts.

2.1. Fly me (sustainably) to the Moon (Worms, Jean-Claude)

There is a need to establish a strong basis for sustainable exploration of the solar system, and in particular of the Moon (COSPAR, 2021), because of the profusion of new, non-conventional public or private stakeholders who are engaged in this new race. Despite varying priorities, it seems that all parties agree that an operational framework needs to be defined and accepted by all, if only to manage liabilities. Science needs to define the topics and schedule for scientific research on, of, and from the Moon. This could lead to an agreement of who can do what, when, where and how on the Moon and elsewhere. More specifically, this will require defining Sites of Special Scientific Interest SSSI (Krolikowski and Elvis, 2024; Committee on the Peaceful Uses of Outer Space, 2025). The goal then is that industry and space agencies, the recipients of this scientific input, will incorporate them in their planning and constraints.

2.2. The COSPAR panel on Planetary Protection: activities for a safe and sustainable space exploration

The Planetary Protection Policy established by the Committee on Space Research (COSPAR) provides an international consultation framework guiding compliance with Article IX of the 1967 Outer Space Treaty (UNOOSA, 1967). The Policy results from collaboration between COSPAR’s Panel on Planetary Protection (PPP), the scientific community, and national space agencies (COSPAR 2018). Its non-binding nature allows flexible updates as scientific knowledge advances (Hedman et al., 2025). As the only international planetary-protection standard, it informs measures against harmful organic-constituent and biological

[1] https://cosparhq.cnes.fr/about/
[2] PEX, https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-exploration-pex/.
[3] IMEWG, https://imewg.org/, is an international coalition of space agencies and institutions for the advancement of the collective human and robotic future on Mars, providing a forum for the coordination of current and future Mars exploration missions.
[4] ILEWG, https://moonbasealliance.com/ilewg, founded in 1994 and reporting to COSPAR, has organized ICEUM International Conferences on Exploration and Utilization of the Moon since 1994 (Arvidson et al., 2010b,a; Balsiger, 1994; Ehrenfreund and Foing, 2006; Foing et al., 1999, 2008; Foing, 2008; Foing et al., 2024).

contamination for all governmental and non-governmental entities, while States remain responsible for national activities under Article VI of the Outer Space Treaty (UNOOSA, 1967; Coustenis et al., 2019b,a, 2023).

The PPP develops, updates, and promotes the COSPAR Policy. It includes 26 members – 12 from space agencies and others representing Scientific Commissions B and F – plus ex-officio and private-sector participants. Planetary protection prevents forward and backward contamination:

- Investigations of extraterrestrial life or precursors are not compromised.
- Earth is protected from potential hazards carried by returning spacecraft.

The Policy is grounded in peer-reviewed science and must support, not restrict, solar system exploration (Coustenis et al., 2025; Hedman et al., 2025). Organizations developing missions ensure compliance, while COSPAR does not prescribe specific implementation methods; States remain accountable.

Recent PPP activities (Coustenis et al., 2025) addressed multiple solar system targets. For small bodies, after considering the 3rd CoPP report,[5] no policy changes were needed (Coustenis et al., 2023). Other categories required updates:

- *The Moon:* Increased exploration interest prompted revised lunar guidelines (2020) based on new findings, stakeholder input, and studies by LEAG and the NASEM Committee on Planetary Protection. The 2021 Policy (COSPAR, 2021) introduced two new subcategories for protecting sensitive areas such as the lunar poles and permanently shadowed regions, while relaxing some reporting requirements elsewhere.
- *Mars:* The Panel examined knowledge gaps for robotic and human missions and reviewed specific projects such as JAXA's MMX Phobos sample-return mission which received outbound Category III and inbound Category V unrestricted Earth return, after independent studies showed low contamination risk (Raulin et al., 2019). The UAE Hope orbiter demonstrated Category III compliance and other mission managers have asked for advice on their compliance with the PP Policy. Despite new data, large areas of Mars remain underexplored, requiring cautious in situ missions to avoid compromising life-detection efforts (Olsson-Francis et al., 2023). COSPAR, NASA, and ESA co-sponsored workshops identifying and prioritizing knowledge gaps for future martian crewed missions (Spry et al., 2024).
- *Venus*: Measurements and studies show Venus' clouds are uninhabitable for Earth life due to low water activity; requirements remain Category II (Zorzano et al., 2023).
- *Icy Worlds*: The Panel is reviewing knowledge of Icy Moons and Ocean Worlds (being defined as Icy Worlds) and proposing updated categorizations based on limits of life linked to temperature and water activity (Doran et al., 2024, 2025).

All policy updates appear in Space Research Today. The PPP will publish a new update to the Policy in January, 2026. Additional reviews are published in scientific journals or shared with stakeholders. Recent updates do not affect current missions; categories for Mars and Icy Worlds (e.g., JUICE, Europa Clipper, Dragonfly) remain Category II or III as previously assigned (Tobie et al., 2025; Lorenz et al., 2025). COSPAR's Policy supports mission needs while applying due diligence and scientific expertise.

2.3. Ethical considerations in space exploration (Smith, Heather)

As the human presence in space expands, one must also consider the ethical implications of humanities expansion in space. When weighing the ethics of a space exploration activity, there are two fundamental questions to consider: Will this activity cause irreversible damage to a celestial body, such as the Moon, Earth, or their inhabitants? And is there a better way to do this activity that reduces or avoids long-term damage? In space science in general and within COSPAR, it was recognized over the past decades that ethical considerations went significantly beyond the original scope of Planetary Protection aimed at preventing biological cross-contamination between Earth and other celestial bodies (see Section 2.2 for an overview of the present activities of the COSPAR Panel on Planetary Protection). Obviously, human-caused impacts and changes to outer space beside biological contamination exist and their ethical implications (also see Section 2.7) should also be investigated. This includes detrimental activities like space debris, atmospheric pollution, light pollution, etc. that should be avoided or minimized in the interest of space exploration, but it also should cover more general considerations how space research and exploration are aligned with and enable sustainable development on Earth and in space. A decision was therefore taken by the COSPAR Leadership to establish panels within COSPAR dealing with such considerations. Examples are the PEX panel and, since 2018, the Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS).

2.4. Advances in Planetary Sustainability (Galli, André and Losch, Andreas)

"Planetary Sustainability" is understood to be the well-established concept of sustainability (Brundtland et al., 1987) combined with two recognitions: (a) Earth is a planet, i.e., we must respect the boundaries of the Earth system outside of which safe operating space can no longer be guaranteed for humanity (Rockström et al., 2009). (b) The planet's space environment is important for sustainability because it may be indispensable for the long-term survival and welfare of humanity (Pass et al. 2006) and because space activities have their own sustainability challenges.[6]

The concept of planetary sustainability was first presented and discussed at the COSPAR Scientific Assembly in 2018 and was elaborated over the past years (Galli and Losch, 2019, 2023). Among interviewed attendees at all COSPAR assemblies since 2018, unanimous consensus was found that outer space plays an important role for the sustainable development on Earth and beyond. Moreover, three main areas of immediate concern regarding planetary sustainability were identified in outer-Earth space: Space debris, the Moon, and Near Earth Objects (closely related to space resources and space mining). One way to raise awareness of sustainability challenges and to negotiate a widely recognized framework ensuring that space exploration supports sustainable development is to add "Space Environment" as an autonomous 18th goal to the 17 Sustainable Development Goals (UN, 2015). This would also prevent the paradox that the use of space to support the 17 Sustainable Development Goals on Earth becomes unsustainable due to the increasing ecological footprint of satellite launches and the finite availability of orbit space (Wilson and Vasile, 2023b). No attendees were arguing against space as an autonomous 18th goal per se, but some pointed out obstacles for implementing this approach (see Section 3.9 for more details).

[5] https://nap.nationalacademies.org/download/26714

[6] www.planetarysustainability.info

2.5. Ethical considerations for analogue fieldwork (Marino, Alessandra)

The presentation on 'Ethical Considerations for analogue fieldwork' takes an approach that echoes how scholarship on planetary sustainability places human activities on Earth firmly on the map of space research. The paper, based on a recent article co-written with astrobiologists from different continents (Marino et al., 2023), suggests that a more just and sustainable future in space can only be built on research that is itself equitable and ethical. The paper identifies three key areas of consideration for scientists: (1) safeguarding the environmental sustainability of precious and sometimes vulnerable ecosystems on Earth used as analogues for other planets; (2) working equitably with local communities and scientists in pursuing knowledge about these environments; (3) respecting knowledge systems that are not one's own, particularly recognizing the depth of Indigenous environmental knowledge. We propose that understanding space and Earth as interconnected domains, mutually shaped by scientific theories and practices, calls for a "planetary ethics" that focuses on this interconnection.

2.6. Applying earth based land-use, and management practices to planetary exploration (Smith, Heather)

The land-use and management policies by various countries and U.S. Agencies, in an effort to balance environmental preservation, science research, resource utilization, and economic interests were characterized and investigated regarding their applicability to cases expected for the lunar surface and other planetary surfaces. Land-use management practices that allow different levels of access to and removal of material should be inversely proportional to any irreversible changes of the planetary body from said activity. The higher the chance of irreversible damage the less likely the activity would be permitted. Similarly, the less likely an activity will cause irreversible changes to the planetary surface the more likely the activity would be permitted. This differing level of land use is similar to the U.S. federal public land-management practices ranging from the most restrictive (National Parks), which allows for the greatest environmental preservation maintaining the science integrity of the site, to the least restrictive (Bureau of Land Management), which considers economic interests. If the impact to the planetary surface of an activity in a given area is not well understood, then activity at that site should remain restricted to environmental preservation and scientific research. Several land management practices restrict the number of persons who can visit a site at a given time. This is applicable to the Lunar surface in a "do no harm or interfere with" approach for current activities at an existing site. Establishing such do no harm or interference guidelines should be through a mutual agreement between the existing party and the incoming party. One main distinction between different protection degrees is how much commercial activity (mining, tourism, etc.) is admissible in a given region. Earth-based land management models, similar to the U.S. federal public land management system, address economic pursuits as well as environmental stewardship while preserving the planetary surface for science research and exploration.

2.7. The problem of space debris and its ethical ramifications (Frueh, Carolin)

Human space faring has expanded the human horizon, fueled scientific knowledge gains, led to significant technological developments and progress. However, it also expanded the human ecological footprint, leaving behind a cluttered space environment. Space debris denotes all the human-made objects that are no longer in use or in any expectation of assuming any useful function, according to the International Astronautical Federation. Space debris is prevalent in the near-Earth regime with the increased scientific and commercial interest in the cislunar region (Black and Frueh, 2025), even wider regions of space will carry the trace of human space fairing in leaving litter behind.

This presentation looked at the specific ethical aspects of space debris generation by considering the current and future effects of space debris, the nationalities involved in space exploration, and the ethical mandate that can be deducted hence. Interpretations of duty ethics were contrasted by utilitarianism, consequentialism, and by a comparison with the Declaration of Human Rights (UN, 1948).

2.8. Airbus views on sustainable exploration (Boithias, Helene)

Airbus Defence and Space have a unique experience in Europe regarding science missions exploring the solar system (e.g. Solar Orbiter, Venus Express, Mars Express, Rosetta, Juice, ExoMars rover) and regarding human space exploration (e.g. Orion European Service Module, contribution to the International Space Station and to Starlab). The responsibility of priming science and exploration missions comes with the responsibility of preserving those worlds for future exploration and the responsibility of ensuring safety for human exploration. The same responsibility lays in preserving the feasibility of Earth-based astronomy. Some key issues related to sustainable space exploration have been addressed early in the history of exploration (e.g. planetary protection), some had to be considered due to rapidly changing boundary conditions (e.g. constellations and space debris), and others are being investigated only recently (e.g. the Moon environment). As an example, through the priming role of the Earth Return Orbiter for the Mars Sample Return campaign, Airbus has experienced first-hand the importance of forward as well as backward planetary protection and how it can impact a mission and its architecture (Cataldo et al., 2024). Due to the importance of these key issues on the future of exploration, Airbus is promoting a responsible approach and is open to regulation aiming to preserve sustainable exploration. These rules need to be elaborated by an internationally recognized independent body such as COSPAR and be applied to every party involved.

2.9. Lunar exploration and sustainability: Challenges, opportunities, and orbital management strategies (Lizy-Destrez, Stéphanie)

The ongoing exploration of space, marked by the continuous dissemination of new scientific knowledge, captivates and engages citizens. Within this context, lunar exploration and potential exploitation stand out as significant priorities for space agencies and private industries. A crucial aspect of this endeavor is the commitment to preserving the lunar environment. This commitment must drive a collective and organized effort to deepen our understanding of the lunar environment, ensure responsible resource utilization, and mitigate the impacts of robotic and human presence. Water is a pivotal resource: it is an important scientific subject for the exploration of the origins and limits of life, but it also represents a potential asset for supporting future exploration missions. Aligned with the goals outlined in the Global Exploration Roadmap of the International Space Exploration Coordination Group (ISECG, 2024), the current decade witnesses a surge in robotic and human lunar exploration. Serving as the initial step towards future human missions to Mars and beyond, lunar exploration encompasses medium-term objectives in exploration, scientific research, and the responsible utilization of lunar resources.

Lunar exploration plays a key role in showcasing new capabilities and leadership from both public and private entities. It empowers the development of innovative technologies as well as fundamental and applied research in several scientific disciplines. With programs like NASA's Artemis and the International Lunar Research Station led by the China National Space Administration, as well as concepts such as lunar villages and bases, the future promises activities ranging from scientific research to lunar resource utilization, astronaut services, and even ventures in business and tourism. These activities rely on a comprehensive range of facilities and operations, including launches from Earth, orbital support infrastructure, lunar landers and transport vehicles, habitats, logistical facilities for energy production, structural materials, and survival systems. Sustaining this endeavor necessitates a responsible, sustainable development approach.

Taking into account the environmental impacts of this lunar exploration trend necessitates a systematic evaluation of mitigation measures for the challenges ahead. This presentation focused on the management of lunar and cislunar orbits, end-of-life strategies for space missions, and the prospect of creating landfills for space debris. Evaluating these aspects involves understanding the scientific assets of the current lunar environment, along with the nature, location, and quantitative extent of potential lunar resources. Effectively and sustainably mitigating these threats revolves around three key priority areas:

1. The management of lunar orbits
2. The responsible management of resources and waste on the lunar surface and in orbit, including the potential creation of landfills for space debris
3. The development of rules and standards in accordance with international space law

2.10. Towards good practices for conducting lunar activities with due regard to science and ethics (Salmeri, Antonino)

This presentation outlined the work conducted by the Lunar Policy Platform (LPP)[7] to create a conducive policy environment enabling the peaceful, safe, and sustainable development of the Moon for the benefit of all humanity. The presentation focused on a proposal for the collaborative establishment of international practices for conducting lunar activities with due regard to scientific, cultural, and ethical interests - the Lunar Science & Ethics Principles (LSEP).

The LSEP would help to clarify whether alleged incompatibilities between scientific and commercial activities on the Moon actually exist by spelling out the main scientific and ethical interests in lunar exploration and outlining what implications they would have on the conduct of other activities, especially commercial, on the Moon. The resulting impact would be a comprehensive recollection of the main scientific, ethical, and cultural interests related to the Moon and concrete guidelines on how to balance them with commercial and national interests, fostering a collaborative approach to lunar development which is mindful of a diversity of interests.

The presentation concluded outlining next steps and inviting respected scientific organizations like COSPAR and the International Astronomical Union, as well as like minded partners such as the Secure World Foundation,[8] to collaborate with LPP for the development of the LSEP throughout the year 2025.

2.11. Lunar resource exchange: Facilitating trade and sustainable utilization of lunar resources (Fazel Hesar, Fatemeh)

This study explored the mineralogical composition of volcanic samples similar to lunar materials (olivine and pyroxene), using hyperspectral imaging to create detailed 3D data cubes. Various unsupervised classification algorithms were employed to classify spectral reflectance profiles. The findings highlight the effectiveness of hyperspectral imaging and advanced classification techniques in mineralogical analysis, enhancing our understanding of lunar geology and aiding future lunar exploration efforts.

This study resulted in an article published after the COSPAR assembly (Fazel Hesar et al., 2025). The study relied on samples from Vulcano, a volcanically active island in the Aeolian archipelago in Italy. The types of unsupervised clustering algorithms to classify the spectral profiles included K-Means, hierarchical clustering, Gaussian mixture models, and spectral clustering. K-Means and hierarchical clustering were found to be the most reliable techniques for this set of samples. The results suggested a predominance of olivine relative to pyroxene. This predominance can be attributed to Vulcano's formation conditions, which are similar to volcanic processes on the Moon. There, olivine-rich compositions are also common in ancient lava flows and impact-melt rocks. These findings provide a deeper context for mineral distribution and formation processes in volcanic landscapes.

2.12. Landing site selection for lunar and martian missions using multi stakeholder-criteria analysis (Garg, Shaifali)

The concept of Analytic Hierarchy Process (AHP) was introduced in economics by Saaty (1980) to set priorities between a diverse set of options and constraints. Over the past decades, AHP has been shown to be a general methodology for decision making in other academic disciplines, too (Forman and Gass, 2001). For the selection of landing sites on celestial bodies, both AHP and other economical models and concepts, such as multilevel optimization, have been applied (Liu et al., 2019; Peña-Asensio et al., 2025).

In this study, AHP was used for the selection of landing sites on the Moon and Mars. The input data including digital elevation map, crater density, surface features, and geological features were obtained from space missions such as Chandrayaan, Lunar Reconnaissance Orbiter, Mars Global Surveyor, and other datasets in the public domain. Based on these data, the algorithm identified regions with optimal conditions for safe and scientifically valuable landings. This study focused on the equatorial regions of the Moon and Mars.

Depending on the weight given to individual parameters (corresponding to a prioritization), the AHP yielded as output least to most favorable landing site locations. Important parameters were landing safety (incl. terrain roughness), illumination conditions, topography, surface composition (incl. abundance of volatiles), scientific interest, potential for exploration, resource utilization, and general economical benefits. For the Moon, specific equatorial regions were identified as most favorable potential landing sites. For Mars, the landing site selection is still work in progress.

2.13. Preparation for astrobiological solar system exploration missions in orbit and on the moon (de Vera, Jean-Pierre)

The use of the lunar orbit and the lunar surface as experiment platforms for investigations on basic research in astronomy, astrobiology, material sciences, medicine and technology tests are prerequisite to allow well prepared further robotic and crewed space missions to Mars and the outer solar systems with its icy ocean worlds. Astrobiology and particularly Applied Astrobiology plays a key role as part of basic/fundamental research because of its cross-related topics in Society relevant key topics such as Health related disciplines like radiation biology, medicine and pharmacological research, Climate Change investigations, Planetary Protection, Biosignature detection and instrument developments and operational support using knowledge from biomimetics/bionics. Also the developments of habitats for crewed missions to the Moon or Mars leans in fact on the basics obtained by astrobiology research which has its focus mainly on terrestrial extremophiles with its potential to be used in multiple disciplines.

2.14. Significance of individual adaptations and morphology in human space exploration (S R, Shine)

Ongoing research has identified a significant correlation between the physiological response and human morphology/racial specificity in extreme environments. Karamapuri and S. R. (2021) have noticed more pronounced increase in core temperature among Western subjects compared to their Indian counterparts when exposed to prolonged hot environments, highlighting the superior adaptability of Indian subjects. Women experienced lower shivering rates and, thus, lower

[7] https://lunarpolicyplatform.org

[8] https://swfound.org/

core temperatures than men for the same degree of cooling (Graham, 1988). Wagner and Heyward (2000) reported differences in bone mineral density, body protein content, subcutaneous fat distribution, and limb-to-trunk proportions between black and white individuals. A study by Farnell et al. (2008) found that, during cold exposure, Caucasian and African American individuals showed distinct variations in core temperature regulation. These morphology and ethnicity-influenced differences underscore the necessity of accounting for these factors in research on physiological changes under microgravity. The hazards linked to a hostile space environment include radiation exposure, compromised sweating, shivering, vasoconstrictive and vasodilatory responses, redistribution in blood flow, and disruptions to circadian rhythm/threshold, among additional considerations. Given the microgravity effects mentioned above and the increasing global interest in expanding human spaceflight programs, it is crucial to take racial specificity and its impact on human thermoregulation under microgravity, as this may result in variations in physical performance in space environments.

2.15. Ceres robotics landers and robotics in support of lunar exploration and science (Shah, Udit and Sims, Michael)

Ceres Robotics[9] is a private space company based in Palo Alto, US, developing landers and robots. The long-term goal of Ceres Robotics is building additional homes for humanity and ecosystems on the Moon, Mars and beyond to bring out the best in human creativity and ambitions. This vision will be enabled by affordable spacecraft and robotic systems including Artificial Intelligence. Ceres Robotics focuses on building smart robots as the tools for the next generation of space explorers and on lander services providing customers with a safe and reliable end-to-end commercial planetary payload solution. Current products include the C-Tower (a remotely deployable and mobile truss mast to support relocatable 50-kW vertical solar arrays on the lunar surface), the CR3 rover primarily intended for the Moon and Mars, and the B5 lunar lander. The latter can be used for landing and orbital missions with a payload weight of up to 1000 kg.

2.16. Innovative funding model for the development of space instruments and scientific payloads for the moon economy (Dubrulle, François and Foing, Bernard)

To advance the development of primary lunar infrastructure, the Qosmosys company[10] explores new funding pathways that integrate both public and private financing instruments. This approach underscores the importance of making the Moon economy sustainable in the long term and profitable for Earth's citizens.

The ambitious goal of conducting scientific research on the Moon necessitates innovative funding models that can overcome the financial barriers associated with space exploration. This presentation introduced a novel approach proposed by Qosmosys, promoting public–private partnerships and which combines government-secured loans with direct investment from Qosmosys for projects that demonstrate commercial potential. This hybrid model aims to facilitate the development and deployment of laboratory space instruments and scientific payloads on the lunar surface, ensuring a sustainable and scalable framework for lunar exploration. Qosmosys' model is predicated on the premise that government-backed loans can significantly reduce the financial risk for investors and stakeholders, making space exploration ventures more appealing. By providing a guarantee, governments can stimulate private sector participation in lunar research, leveraging public funds to attract private investment.

2.17. KIGAM's new direction by establishing the Space Resource Exploration and Utilization Center (Kim, Kyeong)

The Korea Institute of Geoscience and Mineral Resources[11] is the national institute for geological and mineral resources in Korea, established in 1918. With a century-long history, KIGAM has been dedicated to geological research and the development of natural resources for Earth's environment. It has evolved into one of the world's premier geoscience research institutes, leading future Earth research for global prosperity and sustainability. In 2023, KIGAM inaugurated a new division named the Geology and Space Research Division. Within this division, the Space Resource Exploration and Utilization Center was established. KIGAM's first lunar payload is the gamma-ray spectrometer aboard the Korea Pathfinder Lunar Orbiter, known as KPLO GRS (Kim et al., 2018). Currently, KIGAM is in the process of developing a gamma-ray and neutron spectrometer, laser-induced breakdown spectrometer, and volatile extraction demonstrator for lunar surface exploration. These payloads could be deployed for either the Korean Lunar Lander scheduled for 2032 through a competitive process or the Commercial Lunar Payload Services,[12] as well as other international collaborative opportunities. KIGAM is particularly interested in the investigation of space resources, focusing on lunar resources at this time. The institute is also keen on researching in situ resource extraction and utilization. Establishing a space in-situ resource utilization infrastructure in Korea, with both national and international collaboration, is a new research direction for the institute. The active development of research networks with academia, industries, and national institutes related to space resources is underway, forming a research cluster with KIGAM. The institute welcomes new collaborations in the field of space in-situ resource utilization.

2.18. Outcomes of a workshop on perspectives of new entrant space programs on space resources (Chung, Soyoung)

In November 2023, the Republic of Korea and the Secure World Foundation co-organized an International Workshop on Space Resources and Perspectives of New Entrant Space Exploration Programs.[13] The workshop was co-hosted in Daejeon, Korea, by the Korea Aerospace Research Institute, the Korea Institute of Geoscience and Mineral Resources, and the Korea Institute of Civil Engineering and Building Technology. This presentation highlighted the outcomes of the workshop on behalf of the workshop participants. The main goal of the workshop was to build information-sharing links between the space resource community and the new entrant space exploration community. Specific topics of discussion included:

- How to best engage new entrant countries in space resource activities from scientific, technological, commercial, and policy perspectives
- The potential impacts from space resources development that new entrants may be concerned about
- The possible and expected benefits of space resources development

2.19. Apophis T-5 years: Ongoing plans, mission concepts under study and international cooperation (Michel, Patrick)

The close approach of the near-Earth asteroid 99942 Apophis at 32,000 km to Earth on Friday, April 13, 2029, offers a unique opportunity to investigate how the physical properties of an asteroid can

[9] https://www.ceresrobotics.com
[10] https://qosmosys.com/
[11] KIGAM, https://www.kigam.re.kr/english/.
[12] CLPS, https://www.nasa.gov/commercial-lunar-payload-services/.
[13] https://www.kigam.re.kr/board.es?mid=a20401000000&bid=0032&act=view&list_no=58854

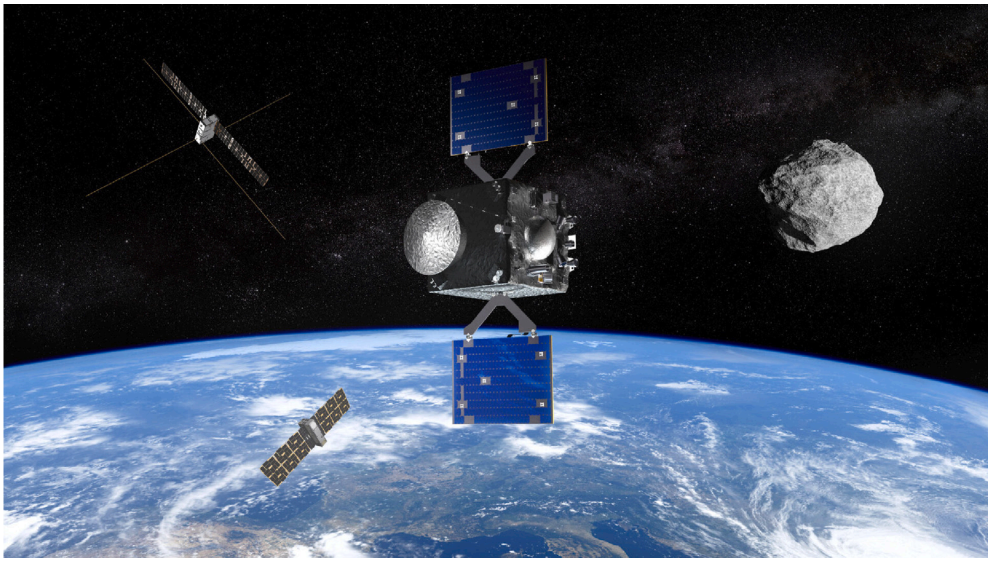

Fig. 1. Artist's impression of RAMSES and its two Cubesats at Apophis (image credit: ESA).

change as a result of external forces from Earth. This opportunity occurs only once per 7500 years. In addition, on April 13, 2029, Apophis will be visible to the naked eye speeding across the evening sky for an estimated 2 billion people spanning western Europe and northern Africa, making this event a source of inspiration for the public. For all these reasons, the RAMSES mission to Apophis is under development at ESA, which will reach the asteroid before its closest approach to the Earth to measure its physical properties and then observe how they potentially change as a result of tidal forces exerted by our planet during the closest approach on April 13, 2029 (see Fig. 1). Later, the OSIRIS-APEX mission by NASA will reach Apophis and measure its post-encounter properties as well as possible long term changes and other projects are under investigation, too. The Apophis flyby in 2029 thus truly is an international endeavor, requiring a well-coordinated cooperation to make the sum of knowledge gained greater than the sum of missions that will eventually investigate the asteroid.

2.20. A new frontiers mission concept for ice giant system exploration (Bolton, Scott)

The ice giants are important targets for future exploration as they are distinctively different from gas giants and terrestrial planets. They mostly consist of heavy elements by mass but contain appreciable hydrogen and helium by molecular number. Their origin is thought to follow that of the gas giants – growth of massive embryos (many Earth masses of ice and rock) within the solar nebula, with a gas-rich envelope arising naturally from the need to establish hydrostatic equilibrium between planet and surrounding nebula. Recent exoplanet discoveries suggest that there are many planets elsewhere that, like Neptune and Uranus, have a hydrogen-rich gaseous envelope, evidently because they formed while a gaseous nebula was present, as must have been the case for our ice giants. The ice giants potentially represent the most common type of exoplanet (Hofstadter et al., 2017).

NASA and ESA are in early stages of considering a flagship mission to the ice giants (National Academies of Sciences, Engineering, and Medicine, 2023). However, the flagship approach has inherent disadvantages with regards to complex management that drives cost and schedule, resulting in much more difficulty in getting a mission approved, designed, built, and launched. In contrast, Juno has demonstrated that compelling outer planet science is possible with minimal technical, programmatic, and cost risk (Bolton et al., 2017). A New Frontiers class concept can permit a return to both ice giants in a much shorter time frame than a flagship at a small fraction of the cost, enabling a relatively contemporaneous comparative study of the ice giants.

To fit within New Frontiers, a concept must be synergistic, blending spacecraft, orbit, payload, observing strategy, mission design, and operations to maintain a simple, straightforward, low-risk, and low-cost approach. This requires a design process that combines engineering, science, and business acumen from the beginning, where cost-conscious payload selection and accommodation, science objectives, spacecraft and mission design are developed in parallel. This design process is the primary reason a PI-led mission can succeed at a fraction of the cost of a flagship without compromising primary science objectives. International partnership is also a key enabling feature for the future exploration of the outer planets. Partnerships may include an atmospheric probe (also see Section 2.21) contributed by ESA, instrumentation on the orbiter and probe from partner countries. At this panel session, a New Frontiers concept for an ice giant orbiter with probe was presented along with proposed roles for international cooperation. The science objectives of this concept include the origin, the interior, the atmosphere, and the magnetosphere of the planet, with its satellites and rings as secondary objectives.

2.21. Generic Entry Probe Program (GEPP) – an international initiative promoting the development of European descent modules dedicated to the in situ exploration of giant planets (Mousis, Olivier and Blanc, Michel)

Mission concepts for the exploration of gas giants and ice giants include both orbiters and entry probes. While orbiters are indispensable in all current concepts, an entry probe in combination with an orbiter is required to study, e.g., the chemical and isotopic composition of the planet in deeper atmospheric layers inaccessible to remote sensing (Mousis et al., 2018, 2022; Vorburger et al., 2020).

The international GEPP consortium studies atmospheric entry probe concepts with payloads that would fit in a typical ESA M-class mission budget (currently 500 M€). The consortium aims at conceptualizing generic planetary entry probes for the giant planets with very few modifications, raising awareness in the international science community of this entry probe concept as part of future international collaborations (for example as part of the future Uranus Orbiter Probe by NASA or other future Flagship or New Frontier missions to the outer planets National Academies of Sciences, Engineering, and Medicine, 2023), and demonstrating that an M-class budget could even fund several entry probes with well-prioritized science objectives. The model payload capabilities of each concept are defined according to a carefully designed science traceability matrix. The GEPP Consortium focuses on two concepts: a highly capable parachute-descent probe including a typical payload of 30 kg of scientific instruments reaching altitudes down to 10 bar pressure level, and a smaller parachute-descent probe designed to address the ESA Cosmic Vision 2050 top priority science objectives (Tacconi et al., 2021).

2.22. OPENS program: How we can change the game of outer planet exploration in a more agile and sustainable way (Yano, Hajime)

In recent years, the "democratization of space" has been a global trend in the Earth orbits. This movement is now expanding to interplanetary space including the Moon and Mars. However, the region of the Solar System beyond Mars is still left out of this development and remains as a destination for large space agencies only that have large launch capabilities, multi-billion dollar mission budgets, and multi-generational commitments of scientists, engineers, and project managers. We have witnessed past and present examples of such missions including Pioneer, Voyager, Galileo, Cassini, Juno, JUICE, and Europa Clipper. Currently, the game appears to continue in the same way according to model missions recommended by the NASA Planetary Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2023) and ESA Voyage 2050 vision (Tacconi et al., 2021).

In the 21st century, the outer planet region attracts strong research motivations from various disciplines like the comparative study with exoplanetary systems and the question about habitability of ocean worlds. Some scientists are therefore developing new research paths of the region through astronomical remote sensing by space telescopes such as JWST and dedicated planetary telescopes like Hisaki, as well as large-scale ground-based telescopes such as ALMA. Remote sensing of the outer planet region from the Earth's vicinity provides shorter turn-around scientific outcomes and more agile follow-on observations than decade- long spacecraft missions. This poses a challenge to the traditional game of deep space exploration as described above.

As a possible solution, JAXA has been developing an innovative mission program called OPENS (Outer Planet Exploration by Novel Micro-Spacecraft). Its first concept nicknamed "OPENS-0" aims at an engineering demonstration mission of key enabling technologies for micro-spacecraft to conduct outer planet exploration (Matsushita et al., 2024). It is planned for launch by an Epsilon-S rocket, which is smaller and lower-cost than its international counterparts, in the late 2020s. Micro-spacecraft are more limited in resources and operational capabilities than legacy outer planet spacecraft. Nevertheless, their lighter mass and smaller size can be advantageous for power and thermal management as well as requirements for delta-V. For example, micro-spacecraft can be fully powered by relatively small solar arrays even in the solar distance beyond Jupiter's orbit. Once the OPENS-0 succeeds in demonstrating that novel micro-spacecraft are capable of outer planet exploration as a different game player from the legacy spacecraft, this expertise will be applied to subsequent missions through various flight opportunities. These include independent missions with small launchers, constellation/swarm configurations of micro-spacecraft with larger launchers, and mothership-daughtership collaboration within a larger international flagship mission to enhance mission capabilities and risk mitigation of the mothership. By this programmatic approach, the OPENS program will realize a higher frequency of outer planet exploration with less cost: technological and scientific advancement will be as fast as astronomical observation, e.g., 10 missions in the next quarter of the century. The OPENS program invites international collaboration to sustain this game-changing process, which will eventually lead the democratization of outer planet exploration for all humankind.

2.23. Space exploration: keeping the momentum (Dautriat, Eric and Blanc, Michel)

This presentation summarized the conclusions of the international conference on Space Exploration organized by the Air and Space Academy in May 2023 in Torino,[14] with a wide participation from students and the support of the Space Generation Advisory Council. Seven specific themes were addressed at this conference, with the overarching theme of keeping the momentum of recent years in solar system exploration:

1. Analysis of the cultural motivations and conditions for robotic and human space exploration
2. Encouragement of innovative ideas from the younger generation
3. Lunar exploration and its environmental aspects
4. Use of "flying machines" on certain planets and moons
5. How to speed up the progress in space exploration and to reach more remote destinations
6. Search for water and its possible use
7. Cooperation between robotic resources and humans

To be a truly sustainable effort, keeping up the momentum must be combined with an ethical approach, whereby engineering and scientific considerations are connected with societal values and education. Space discoveries that are accessible to the wider public ensure the interest and involvement of citizens – and therefore, ultimately, their support. European agencies and governments should more openly address the philosophical and cultural bedrocks of space exploration and create a framework for implementation of cheaper, simpler missions to be carried out by small entities or universities and open to a large number of new, young contributors (with flying machines in planetary atmospheres being a prime example). Moreover, going faster to remote destinations, through appropriate propulsion means, is also a condition for "keeping the momentum" (also see Sections 2.20 and 2.22).

Lunar exploration, and possibly utilization of lunar resources, is also beneficial in this respect if proper concern is given to preserving the lunar environment. To this end, understanding the Moon's environment is crucial to take informed and rational decisions on resource usage (e.g. the search for water) and mitigating impacts of a robotic and/or human presence (see for instance the Planetary Protection Policy update for the Moon by Ehrenfreund et al., 2024). International cooperation is omnipresent in all these discussions, especially within the European space community. This cooperation should be seen as an objective in itself and a political imperative for humanity, all the more so in times of enhanced geopolitical tensions. Cooperation brings a specific value that goes far beyond the simple goal of sharing costs: space exploration is an unrivaled area to bring the best of humanity with a common goal to the fore.

3. Current main and emerging topics of concern and consideration

From the panel session presentations (Section 2) and from informal discussions during the COSPAR Scientific Assembly within PEX and other panels, ten current topics of interest and concern for sustainable space exploration can be identified. We summarize them here; the ordering does not imply a prioritization. International collaboration to find practicable and widely accepted solutions to challenges is an overarching theme to all the following topics.

[14] https://www.aerosociety.com/events-calendar/aae-international-conference-on-space-exploration/

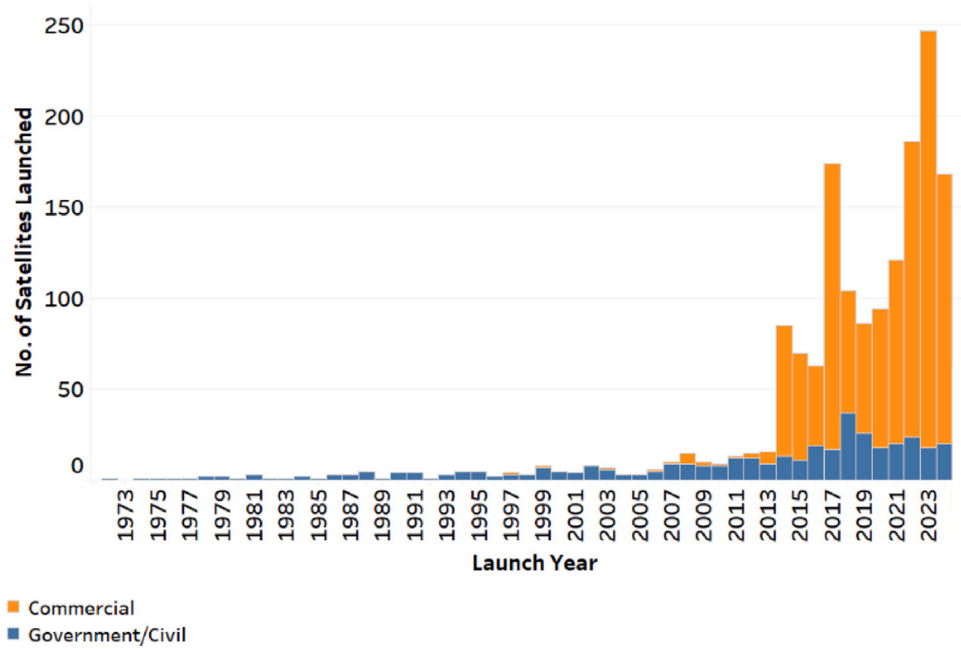

Fig. 2. Number of commercial satellites (orange) and government satellites (blue) launched per year from 1972 until 2024. Figure adapted from US Geological Survey (https://www.usgs.gov/media/images/chart-commercial-government-civil-satellites-launched).

3.1. Space debris

The rapidly evolving situation of space debris was pointed out as a great concern to space exploration by several presentations and is also often used as typical example of environmental problems or example of the tragedy of the commons in space beyond Earth (Gable, 2007). In terms of policy making, space agencies (ESA, 2022) and national bodies have implemented guidelines or even rules (FCC, 2022) to counteract the growth of orbital debris, but two question marks remain: Are these rules sufficient, if all actors implement them, to make a run-away collision cascade in the 21st century (so-called Kessler syndrome Kessler and Cour-Palais, 1978) very unlikely and (2) are they feasible and acted upon by all spacefaring actors? Of great relevance for question (2) is the private sector since more than 80% of all newly launched satellites since 2017 were commercial satellites (see Fig. 2) and – to a lesser extent – armed forces. Liang et al. (2024) found in their model that "a launch rate of 1500 satellites per year [current actual launch rate] is simply too high for space to be sustainable long-term [throughout the 21st century] even with the 5-year rule [to de-orbit satellites] in place" if no active debris removal techniques are implemented.

The most urgent task appears to be to reduce the growth rate of space debris to zero by a better policy, but in the medium term active removal/de-orbiting of some larger debris objects may also become necessary. The ultima ratio, which all actors want to avoid, would be to limit the number of new satellite launches. The potential impact on Earth's atmosphere of de-orbiting thousands of satellites per year should also be considered in a complete life cycle assessment (see Colombo et al., 2017 and Section 3.2).

Similarly, the matter of cis-lunar space debris is likely to become an issue with the increase of planned public and private missions to the Moon. Between the geostationary region and the Moon, including the Earth-Moon Lagrange points, debris generation is unregulated so far. A single fragmentation in cis-lunar space could result in fragments anywhere between the lunar surface and the Earth, colliding with near-Earth space assets. Passivation of upper stages is a well-established mitigation practice in near-Earth space and could be easily accomplished for cis-lunar upper stages (Frueh et al., 2021).

3.2. Further sustainability aspects of space industry, in particular the potential of atmospheric pollution

The topic of potentially detrimental impacts of space exploration and industry and how to calculate them via life cycle assessment is not per se new (see Wilson et al., 2022; Wilson and Vasile, 2023a; Udriot et al., 2023; Barker et al., 2024 and references therein). However, over the past few years the question about atmospheric impacts of space exploration have come to the fore, in particular the question how de-orbiting thousands of satellites per year may affect the thermosphere, the lower atmosphere, and potentially the global climate.

The main take-home message of the discussions at the PEX sessions (in accordance with the recommendations by Wilson et al., 2022; Udriot et al., 2023) was that more in-situ measurements and data for life cycle assessments are urgently needed to make reliable statements on the potential severity of these impacts. For instance, the foreseen increase of satellites in low earth orbit could cause up to half of stratospheric sulfuric acid particles to contain metals from re-entering satellites within the next few decades. The influence of this level of metallic content on the properties of stratospheric aerosol is unknown (Murphy et al., 2023).

3.3. Preservation of dark and quiet skies

The increase of launch opportunities and decrease of launch cost both represents opportunities and challenges for space research. For research dependent on satellites, the benefits dominate, whereas for ground-based astronomy the drawbacks outweigh the benefits. For radio-astronomy, the preservation of a radio-quiet sky with as few radio transmissions from satellites at relevant frequencies as possible is crucial. On a wider level, the reduced visibility of the natural night sky may be considered a cultural loss [REF?]. Additional artificial light sources in the sky may also adversely affect Earth's biosphere although the light pollution of cities and infrastructure is so far the main culprit in this respect.

In 2022, the concern of dark and quiet skies was brought up for the first time as a formal agenda item by the United Nations thanks to the initiative of, among others, the International Astronomical Union, the European Southern Observatory, and the Square Kilometre Array

Observatory. The petitioners submitted a paper to the UN Committee on the Peaceful Uses of Outer Space (COPUOS) for better protections for the dark and radio-quiet skies, which was discussed at the 59th session of the COPUOS Science and Technical Subcommittee (COPUOS, 2022). The paper identified three artificial interferences that negatively impact on astronomical observations: urban illumination or artificial light at night; optical/infrared trails of the satellites in low Earth orbit; and radio transmission by ground and space emitters, especially from satellites in low Earth orbit.

For present and future space programs involving satellites in Earth orbit, the needs of astronomy, of the wider public and of the biosphere must be taken into account. The COPUOS document offers valuable guidance on how to mitigate the adverse impact of satellites both for astronomers, for satellite industry, and for regulatory bodies. Transparent discussion and close collaboration between the different stakeholders is crucial in this respect; COSPAR with its panels offers one of the venues where these discussions can be held.

3.4. The moon

The Moon is vital for all life on Earth, in particular thanks to its stabilizing effect on the Earth's orbit. Moreover, the Moon is part of the cultural heritage of all humanity. It has always reminded humans that outer space is just above our heads, already long time before the dawn of space age. Over the last 60 years, the Moon has turned out to be crucial for space science and exploration for at least three reasons.

First, the Moon is a fascinating world which has close links to the Earth, although it appears completely different to our planet. The International Lunar Exploration Working Group put the science aspect as follows: "Lunar studies are essential to understanding of our planet Earth, because the Moon and the Earth have been dynamically and chemically connected from birth. Furthermore, the Moon retains a record of the most ancient geological events in our part of the solar system. From the continuous lunar meteoroid impact history, we can further understand the Earth bombardment history and its key role in the origin and evolution of life". (Foing et al., 1999) Currently, there are still outstanding questions about the Moon regarding its inner structure and the implications for the origin and evolution of the Earth-Moon system, regarding the late heavy bombardment and impact processes and regolith evolution in general, and regarding the nature and origin of volatiles from the interior to the exosphere.

Second, the Moon is becoming an attractive destination for human activities, ranging from science to economy driven exploration to maybe even tourism. The current legal regime for the Moon is mainly set out in the Outer Space Treaty (UNOOSA, 1967) and the more recent Moon Agreement (UNOOSA, 1979). While this framework is satisfactory for current missions, it may require further clarification for future exploration. A particularly interesting point concerns the potential utilization of lunar resources such as water ice or regolith as building material. The question of resource utilization has a scientific dimension, but also needs to be studied under economic and societal-cultural aspects. We endorse the recommendations from previous ICEUM International Conferences on Exploration and Utilization of the Moon, which include engaging the wider public (in particular the young generation), open access to information and lunar data (historic and new), and discussion of political and legal concerns about lunar exploration and resource utilization (Arvidson et al., 2010b,a; Foing et al., 2008). Lunar orbiters, robotic landers, rovers, and pressurized lunar rover projects are important steps that can create opportunities for international collaboration, including a coordinated village of robotic precursors and assistants to crew missions. Lunar exploration projects should strive towards closer international and inter-company cooperation, while still allowing areas of competition to keep the process active, and time and cost effective (Foing et al., 2023; Foing, 2024). Exploration requires international cooperation and sharing of data and results in order to be done in a cost-effective manner. Public access to raw and derived (geophysical units) data products using consistent formats and coordinate systems will maximize return on investment.

Third, the Moon is a unique testbed and stepping stone for humanity's venture into the wider solar system beyond low Earth orbit. Human and robotic exploration of the Moon will teach us valuable general lessons, also for later ventures to other destinations like Mars (Mendell, 2005). We have to learn how to further improve navigation capabilities and data relay assets to support future robotic and human exploration. New concepts and new methods for transportation have attracted much attention and are of great potential. The Moon will also teach us how to build durable and sustainable life support systems in an environment hostile to terrestrial life. We note a large interest in closed ecological life support systems for Moon and Mars bases and recommend further research and development (Foing et al., 2024, 2023; Foing, 2024). Terrestrial analogues research sites and facilities should be developed and used for technology demonstrations, comparative geology, human performance research, and public outreach. Specifically for the lunar environment, further research is needed on the lunar dust and how it may affect humans and human habitats on the Moon. We should also make effective use of the lunar orbit space as a stepping stone for exploration and human spaceflight beyond low Earth orbit.

3.5. Mars

Mars occupies a special and unique place in the landscape of exploration: on one hand, it is, along with ocean moons, the priority target in the quest for extinct or extant life in the Solar System. As such, Mars represents a prime science destination that must be carefully investigated by duly prepared robotic missions meeting the highest level of planetary protection requirements. On the other hand, Mars is also, with the Moon, the only place where a temporary or prolonged human presence can be foreseen and planned for the coming decades. However, the science community strongly expresses the opinion that these two objectives are mutually exclusive: as long as the search for life at Mars remains a relevant scientific objective, this excludes the simultaneous presence of human exploration ventures, because they could not possibly meet the required planetary protection requirements. Even more, if signatures of life are finally discovered by robotic probes on Mars, revealing that a "second genesis of Life" occurred in the Solar System, this would represent a major scientific breakthrough that would immediately turn Mars into the major natural laboratory for understanding the origin and early development of life, and/or the transition from chemistry to biology. In such an extraordinary circumstance, planetary scientists believe that the pristine natural environment of Mars should be protected by all means, and that any human interference with this precious environment should be delayed or duly constrained to avoid any possible human contamination.

As a consequence, securing the respective timing and planning of robotic and human missions should be given special attention and care in a strongly needed international management of the future of Mars exploration. The search of potential past and present life on Mars must be intensified now, before the first human mission may bring in more terrestrial contamination.

3.6. Space resources

COSPAR participants expressed their support to the principle that the development of space exploration must go along with a responsible use of space resources, and that promoting and implementing a responsible use of space resources is crucial for sustainable space exploration. If possible, space resources should be used in a reversible manner. This is feasible for orbit space, but is much more difficult when it comes to water ice or soil in the example of lunar exploration. Consumption, i.e., the irreversible usage of resources, must be carefully considered given the prerogative of sustainable development to meet the needs of the present “without compromising the ability of future generations to meet their own needs”. (Brundtland et al., 1987).

Space research and exploration always requires space resources to some extent. Any satellite, whether scientific or commercial, requires a safe space in orbit. The fact that an orbit slot in itself is a limited space resource has been known for decades but policy making still has to catch up with this insight (see Section 3.1). Beside Earth orbit space, the other immediate regions of interest regarding space resources are the Moon and Near Earth Objects. Here, rewards and conflicts are plausible already in the following years and decade. Among lunar resources, water ice appears to be the most desired resource to enable a human and robotic presence on the Moon at a more feasible cost. Lunar soil as building material (see Section 3.4) and Ti, Fe, Al, and rare earth elements are also being considered (Espejel et al., 2023).

At present, there is little positive national or international law regulating space resources and their utilization. Likewise, there are no accepted practices yet to establish customary law: The Moon Agreement (UNOOSA, 1979) is an international treaty but was not signed by a majority of states. The statements on lunar resource utilization in the more recent Artemis Accords initiated by the US and in China’s International Lunar Research Station (ILRS[15]) might pave the way to establish customary law, but this remains to be seen. The content and implications of the two frameworks have been investigated by several scientific and policy specialists in the recent past (O’Brien, 2020; Stimers and Dinegar, 2020; Swiney and Hernandez, 2022; Anderson et al., 2023; Wu, 2023; Salmeri, 2023). We give a short overview of the Artemis Accords and the ILRS here as they are closely linked to the overarching discussion of space resource utilization.

The Artemis Accords are a multilateral political document originally drafted by a group of eight Countries under the leadership of the United States, currently counting 60 States Signatories. The Accords outline 11 fundamental principles for cooperation in the civil exploration and use of the Moon for peaceful purposes. The goal of the Accords is to harmonize and foster the operationalization of legal obligations laid down in the Outer Space Treaty (UNOOSA, 1967) as applicable to lunar activities; and in fact all principles outlined in the Accords explicitly refer to one or more provisions of the Outer Space Treaty. In terms of their status, the Accords express a voluntary political commitment and can therefore not be considered as an internationally binding agreement. They are also different from the Artemis Program, which is an international lunar program promoted by NASA. While signing the Artemis Accords is considered to be a pre-requisite to participate in the Artemis Program, signing the document does not guarantee that.

There is no equivalent document to the Artemis Accords within the ILRS, which is an international lunar program promoted by the China National Space Agency (CNSA). The ILRS program is managed through a series of bilateral internationally binding agreements concluded between CNSA and the other participating Countries (currently 10). The ILRS Agreements are focused on the contributions and obligations of both CNSA and the corresponding party within the development and execution of the ILRS, and do not include any policy principle. Operational guidance on the execution of the ILRS is provided in the “ILRS Guide for Partnerships”, originally developed by CNSA in 2021 and updated in 2024. As of 2023, CNSA developed a “cooperation initiative” managed by its Deep Space Exploration Laboratory which outlines six high level principles for cooperation within the ILRS program. The ILRS Cooperation Principles are also grounded in the Outer Space Treaty and aim at supporting its further development and implementation within the context of lunar activities.

After the COSPAR 2024 Assembly, in October 2025, the Lunar Policy Platform (see Section 2.10) and the Korean Aerospace Research Institute hosted a closed door seminar to shed more light on the origins and content of both the Artemis Accords and ILRS Cooperation Principles. The seminar saw the participation of two speakers from the United States and China who played a key role in the development of their respective document. After two initial presentations, the speakers engaged in a dynamic Q&A with the audience aimed also at highlighting similarities and differences between the two documents. As a result of that conversation, it was found that the two documents share the same legal grounding in the Outer Space Treaty and the same vision of enabling international cooperation in the peaceful exploration and use of the Moon. The documents also contain similar provisions on peaceful uses, international cooperation, openness, and scientific data sharing. Three key differences concerned the topics of space resources, heritage protection, and safety zones, which are all currently under discussion at the multilateral level within the COPUOS.

To conclude, the dearth of international regulations and customary law poses both an opportunity and a risk to parties interested in resource utilization and, more specifically, space mining. As Murnane (2023) put it: “There remains a great deal of ambiguity surrounding many of the legal principles applicable to space resources, including the provisions of laws and treaties that specifically discuss the subject. Therefore, the decisions of a relatively small number of authorities and the actions of a few operators could have a profound effect upon the development of space-resource laws and practices over the next several decades”. As a consequence, all stakeholders involved in space exploration see the imminent pressure for widely accepted guidelines and legal clarification on an international level so that space resource utilization benefits all humankind and strikes a balance between potentially conflicting needs of different interest groups.

3.7. Need for a strategic framework for the future exploration of the outer solar system

While lunar and Martian exploration rightly receives significant attention and international consensus, a comprehensive scientific understanding of our solar system’s formation, evolution, and potential habitable environments requires a broader focus encompassing all categories of mission targets. The outer solar system is particularly critical in this endeavor. Giant planet systems and their potential Ocean Worlds, Trans-Neptunian Objects, and heliospheric boundaries provide a unique window into the cosmic processes governing the formation and evolution of planetary bodies and the emergence of habitable worlds. They also provide the best accessible templates for the most common classes of exoplanets, i.e., sub neptunes and hot jupiters. For all these reasons, outer solar system objects bear a particular importance in comparative planetology: exploring these distant targets is essential to complement the partial lessons learned from terrestrial planets alone, connect the solar system to the myriad of exoplanetary systems being discovered, and thus better understand our place in the Universe.

Missions beyond Jupiter (i.e., beyond 5 au heliocentric distance) present profound challenges that distinguish them from inner solar system exploration. These include:

- *Power Generation:* While the Juno mission (Bolton et al., 2017) has successfully proven the use of solar power at Jupiter, it becomes impractical at greater distances without major technological advances. Radioisotope Thermoelectric Generators have historically powered missions like Voyager and Cassini, but their development has been delayed or canceled, creating a critical technology gap for future missions.
- *Mission Duration and Cost:* The long travel times, coupled with extended development and approval phases, result in high-cost, long-duration missions. This creates significant programmatic and political funding challenges.

[15] https://www.cnsa.gov.cn/english/n6465652/n6465653/c6812150/content.html

- *Engineering Longevity and Design:* The spacecraft themselves must be designed for exceptional longevity. The use of gravity assists to reduce travel time or increase payload mass introduces additional complexities for thermal control and limits launch opportunities to specific planetary alignments.

To address these main challenges, new propulsion and power source technologies, along with new types of mission and platform architectures, are needed for the next generations of outer solar system exploration missions to reduce mission duration cost and increase the number of flight opportunities.

Currently, two primary mission archetypes exist within space programs like NASA's: large, complex Flagships and smaller, Principal Investigator (PI)-led missions. Flagship Missions (e.g., Cassini-Huygens, Europa Clipper) have the advantage of being able to develop and implement new, complex technologies, as well as complex mission architectures including atmospheric probes and landers. PI-led Missions (e.g., Juno, New Horizons), on the other hand, have proven to be a highly efficient and cost-effective alternative. They can often adopt technologies first pioneered by Flagships, thereby reducing risk and cost. The key disadvantage of the Flagship model is its high cost and the associated difficulty in securing sustained political and financial support for decades-long projects. A balanced exploration program must therefore leverage the strengths of both approaches.

To keep the dream of deep space exploration accessible to a wide spectrum of nations, space organizations, and scientific communities while keeping the momentum that outer solar system exploration deserves, the global space program must offer a broader spectrum of opportunities than it currently does. This includes: (1) a broad portfolio of mission sizes, from small, flexible missions to large, ambitious Flagships, (2) the ability for entities to contribute at various levels, from intellectual input and small instruments to providing entire platforms, and (3) inclusive access fostered through broad, diverse, and international collaborations.

Given the immense technical, financial, and programmatic challenges, no single nation can sustain a comprehensive program of outer solar system exploration alone. A coordinated international framework is essential to create a sustained pipeline of missions. Such a framework can pool resources, share technological expertise, distribute risk, and ensure a steady cadence of missions that would be unattainable for any single agency. This is the most viable path to addressing over the long term the key science objectives in solar system and planetary science that require exploration of the outer solar system and its boundaries with the interstellar medium.

COSPAR is uniquely positioned to advocate for and facilitate the emergence of this required international cooperation framework. COSPAR should play a vital role in deep space exploration by acting as a neutral forum for international discussions on strategy and collaboration, by advocating for the conditions necessary for a diverse and inclusive exploration ecosystem, and by developing and maintaining a strategic roadmap for science technologies and international cooperation in Deep Space exploration. Such a line of action should constitute one of the "Stepping Stones" to be promoted in the next edition of the COSPAR Exploration Roadmap (see Section 3.10). By promoting this approach, COSPAR will help catalyze the international consensus and long-term planning needed to unlock the secrets of the outer solar system.

3.8. Human spaceflight and human exploration

Several aspects of human spaceflight, from planetary protection considerations to adaptation to microgravity, have become more visible over the past years. This enhanced awareness is driven by the growing commitment from a larger set of nations in human spaceflight programs and by the imminent return of humans to the Moon and more long-term plans and initiatives for permanent human presence (be it for scientific, commercial, or touristic reasons) on the Moon and other celestial bodies (such as Mars).

In this renaissance of human spaceflight our scientific knowledge of these planetary bodies through human exploration will greatly expand our understanding of the planetary bodies within our solar system including Earth. In addition to an increase in understanding of fundamental science, the development of systems to support human exploration on another planetary body can be applied to Earth to minimize resources, thus increasing environmental stewardship. To have the greatest impact on science, exploration, and society human spaceflight and exploration must be an international collaborative effort. Based on our experience with space stations in Low-Earth Orbit, we emphasize two aspects of human spaceflight and exploration: Space exploration is best achieved through an international, collaborative effort and the technologies developed for human spaceflight and exploration benefit Earth.

3.9. Space as an additional 18th Sustainable Development Goal

Space is crucial for several of the 17 United Nations Sustainable Development Goals (SDG, UN, 2015) but currently does not represent an independent SDG. This could be amended by declaring space as an autonomous 18th SDG (see Fig. 3 and propositions by, e.g., Losch et al., 2024; Zimon et al., 2024). Detailed targets of such an 18th SDG could be:

1. Reduce space debris
2. Integrate sustainability measures into national policies, strategies and planning
3. Scientific knowledge and research for sustainable exploration and use of outer space
4. Sustainable financing of space exploration
5. International framework on space mining issues including equitable share of the costs and benefits
6. Education and International Cooperation for sustainable space activities
7. International space traffic management and sharing of information on space
8. Universal adoption of COPUOS Space Law
9. Preservation of the pristine night (and day) sky

Joining in with these academic studies and initiatives, the Space Renaissance International[16] and the National Space Society,[17] in partnership with many other space organizations, urge UN COPUOS State Parties to develop and introduce a resolution for a Space 18th Sustainable Development Goal (SDG), calling for the expansion of community life into space to achieve universal and sustainable development for the whole humanity, life, and the life support environment, on Earth and beyond. The underlying reason is that only by expanding the domain of life into space can we fulfill the 17 SDGs on Earth in the long term.[18]

Because the number of SDGs will most likely not be formally amended before the nominal end of their cycle by 2030, additional efforts from the space community are necessary in the intermediate years. For instance, space education should be strengthened in educational curricula at university level but also primary and secondary school level stages to ignite the consciousness of preserving space as common good for everybody. The detailed list of goals and how to implement them has to remain an active topic so the recommendations of the space research community are ready when potential successor programs to the 2030 Agenda for Sustainable Development will be discussed among UN departments or committees. The PEX panel supports the notion of Space as an 18th independent SDG and, equivalently, as an autonomous goal of sustainable development for the epoch beyond 2030.

[16] https://spacerenaissance.space/

[17] https://nss.org/

[18] https://space18thsdg.space/

Fig. 3. The 17 goals for Sustainable Development as defined by the UN, plus the space environment as a potential 18th goal (design by Karl Herweg).

3.10. COSPAR space exploration roadmap

In view of the discussions at the COSPAR Scientific Assembly 2024 and the current developments in space exploration summarized in this paper, the interest for defining a new edition of the COSPAR Exploration Roadmap, building on the previous edition (Ehrenfreund et al., 2012) has grown. Building this new Roadmap will involve the whole scientific structure of COSPAR, and PEX will play a central role in the coordination of this new exercise. This overhaul will take into account the evolution of the objectives, scope and stakeholders of solar system exploration, the broad spectrum of scientific disciplines and technology areas contributing to exploration, and encompass all provinces of the Solar System where novel exploration is taking place. The roadmap will also build on an analysis of the contributions of other foresight exercises such as IAA (Huntress et al., 2006), the ISECG Global Exploration Roadmap (ISECG, 2024), and community-driven foresights like Blanc et al. (2023) and assess their applicability to the COSPAR roadmap. Work on this updated COSPAR-driven roadmap has begun in 2025 under the guidance of the PEX panel, with representatives of COSPAR commissions and panels joining; interested colleagues from all science and technology backgrounds are eagerly invited to participate by contacting the PEX chair and vice-chairs Michel Blanc, Heather Smith, Bernard Foing, and André Galli.[19]

Specific PEX sessions are planned for the COSPAR Exploration Symposium in Nicosia Cyprus in November 2025[20] and for the next COSPAR Scientific Assembly in Florence in August 2026.[21]

4. Conclusions

The interest in space exploration is set to increase in the coming years. Differing goals of the various space actors (scientists, NGOs, commercial actors, space agencies, and policy makers) may lead to contradictory demands. It is therefore crucial to ensure various robust and mutually trusted platforms to discuss and implement space policy among all involved nations and different groups of stakeholders. Within space research, COSPAR and its panels are well set up to act as such a platform.

[19] https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-exploration-pex/
[20] https://www.cospar-assembly.org/admin/congress.php?congress=12
[21] https://cospar2026.org/ https://www.cospar-assembly.org/assembly.php

CRediT authorship contribution statement

André Galli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Conceptualization. **Heather Smith:** Writing – review & editing, Writing – original draft, Validation. **Michel Blanc:** Writing – review & editing, Writing – original draft, Validation. **Bernard Foing:** Writing – review & editing, Writing – original draft, Validation. **Hélène Boithias:** Writing – review & editing, Writing – original draft. **Scott J. Bolton:** Writing – review & editing, Writing – original draft. **Soyoung Chung:** Writing – review & editing, Writing – original draft. **Athena Coustenis:** Writing – review & editing, Writing – original draft. **Eric Dautriat:** Writing – review & editing, Writing – original draft. **Jean-Pierre de Vera:** Writing – review & editing, Writing – original draft. **Peter Doran:** Writing – review & editing, Writing – original draft. **François Dubrulle:** Writing – review & editing, Writing – original draft. **Fatemeh Fazel Hesar:** Writing – review & editing, Writing – original draft. **Carolin Frueh:** Writing – review & editing, Writing – original draft. **Shaifali Garg:** Writing – review & editing, Writing – original draft. **Niklas Hedman:** Writing – review & editing, Writing – original draft. **Kyeong J. Kim:** Writing – review & editing, Writing – original draft. **Stéphanie Lizy-Destrez:** Writing – review & editing, Writing – original draft. **Andreas Losch:** Writing – review & editing, Writing – original draft. **Alessandra Marino:** Writing – review & editing, Writing – original draft. **Christopher McKay:** Writing – review & editing, Writing – original draft. **Patrick Michel:** Writing – review & editing, Writing – original draft. **Olivier Mousis:** Writing – review & editing, Writing – original draft. **Antonino Salmeri:** Writing – review & editing, Writing – original draft. **Udit Shah:** Writing – review & editing, Writing – original draft. **Shine S. R.:** Writing – review & editing, Writing – original draft. **Michael Sims:** Writing – review & editing, Writing – original draft. **Jean-Claude Worms:** Writing – review & editing, Writing – original draft. **Hajime Yano:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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