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Editorial: Editor's challenge in planetary science: the future of planetary exploration and the next generation of planetary missions

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Editorial on the Research Topic
Editor's challenge in planetary science: the future of planetary exploration and the next generation of planetary missions

I am thrilled to announce the inaugural editor's challenge in the Planetary Science section, focusing on the future of planetary exploration and the upcoming generation of planetary missions. This compilation highlights the exceptional work contributed by members of the Editorial Board of the Planetary Science section, as well as contributors recommended by the Specialty Chief Editor of the Planetary Science section.

In recent years, an array of planetary and cometary missions -from the Sun (with NASA's Parker probe making close approaches and ESA's Solar Orbiter) to the outer Solar System where Juice is on its way to Jupiter- has played a crucial role in reshaping the landscape of planetary science, significantly enhancing our understanding of the Solar System. Looking ahead, the promise of both robotic and human planetary exploration initiatives, coupled with upcoming planetary missions such as EnVision, Comet Interceptor, and the ExoMars Rover, etc., have the potential to deepen our insights into the Solar System and beyond. These endeavors are anticipated to make significant progress in diverse research domains and technological advancements. Proposals addressing challenges related to mission execution, data interpretation, development of mission concepts, and more are at the forefront of advancing space exploration.

The impact of such advancements extends beyond the scientific community. These missions serve as a wellspring of inspiration for the next-generation of scientists and engineers, fostering a sense of curiosity and excitement. The high level of public enthusiasm surrounding these endeavors underscores their significance and the universal intrigue in unraveling the mysteries of our cosmic neighborhood.

Guided by influential reports such as the US planetary science decadal survey and ESA's Voyage-2050 strategy (Favata et al., 2021; National Academies of Sciences and Medicine, 2023), the forthcoming decade holds the promise of groundbreaking missions and research initiatives. These strategic documents outline key research areas, including the origins of the Solar System, worlds and processes, life and habitability, and cross-cutting exoplanetary Research Topic. By establishing a robust foundation for future exploration, these recommendations set the stage for a new era of discovery and technological innovation, shaping our understanding of the cosmos in the years to come.

This article Research Topic comprises five distinct manuscripts, featuring a blend of two original articles, one review, one mini-review, and one perspective. Within this diverse assembly, we explore the forefront of planetary science, delving into cutting-edge research and engaging in critical discussions. The articles cover an advanced data analysis technique applied to mass spectrometry on ocean worlds, an examination of the ethical and practical considerations surrounding the protection of celestial bodies from potential biological contamination, the transformative role of artificial intelligence in remote sensing and geomorphology, a comprehensive overview of radiative transfer and inversion codes in the study of planetary atmospheres, and insights into the exciting possibilities for upcoming missions to Venus. Together, these articles make substantial contributions to the ongoing discourse, fostering advancements within the dynamic field of planetary science.

The papers in this Research Topic are briefly described as follows: in the first paper, Da Poian et al. discusses challenges faced by some upcoming and proposed missions to ocean worlds like Europa, Enceladus, and Titan in evaluating habitability and potential life. To overcome communication challenges and technology limitations, the authors propose leveraging data science and unsupervised machine learning techniques on isotope ratio mass spectrometry data (IRMS) from volatile laboratory analogs of Europa and Enceladus seawaters. The primary objective is to assess whether mass spectra of volatile gases could provide information about seawater composition and potential biosignatures. The study focuses on exploratory data analysis (EDA), a crucial unsupervised learning step, to understand data patterns, correlation structures, variable significance, and identify irregularities. Dimensionality reduction methods like Uniform Manifold Approximation and Projection (UMAP) and Principal Component Analysis (PCA) are compared, along with clustering algorithms to categorize data-driven groups in the ocean worlds analog IRMS data. This research promises to stablish the foundation for future science autonomy goals, aiming to use similar automated machine learning tools onboard spacecraft for prioritizing data transmissions in bandwidth-limited outer Solar System missions.

In the second paper, a review by Coustenis et al. outlines the significance of planetary protection, a comprehensive set of measures established at the international level to safeguard scientific investigation during space exploration. With the increasing accessibility of space and a surge in diverse projects involving robotics, sample return, and human exploration, the responsibility to preserve the pristine environments of celestial bodies and our own biosphere becomes paramount. The Committee on Space Research (COSPAR) plays a central role in providing the international standard for planetary protection and serves as a forum for global consultation. While the COSPAR Planetary Protection Policy is not legally binding, it is internationally endorsed, offering a standard with associated requirements and guidelines to support states in complying with the United Nations Outer Space Treaty[1]. The primary objective is to prevent contamination that could compromise the search for extraterrestrial life and protect Earth from potential threats posed by returned interplanetary mission samples. The COSPAR Policy categorizes space missions into five groups, depending on the target and objective of the specific space mission, each associated with contamination control requirements of varying rigor. Regular assessments and updates to the Policy, driven by new scientific findings and the evolving space exploration landscape, ensure its relevance. The COSPAR Panel on Planetary Protection (PPP), comprising scientists, agency representatives, and space experts, plays a crucial role in supporting and revising the Policy to address the specific needs of individual space missions, ensuring the sustainable exploration of the Solar System. Further details about the Panel's activities can be found at https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/.

In the third paper, Mall et al. addresses the application of artificial intelligence (AI) in recognizing lunar boulders from images captured by a lunar orbiter, aiming to create a comprehensive lunar map featuring boulders' tracks on the regolith. While AI offers the potential to reduce costs and enhance reproducibility in geomorphological mapping, this research compares the AI-generated results with those identified by a human analyst (HA). The study involves 181 lunar craters across the lunar surface. Surprisingly, the AI workflow significantly underestimates the number of identified boulders compared to the HA's findings, detecting less than one-fifth of them. The focus is not on absolute sensitivities but on understanding the differences between the two approaches and suggesting improvements for the machine learning approach. The research underscores the need for a critical assessment of AI results to ensure the reliability of future network architectures in delivering accurate geomorphological maps.

A mini-review by Rengel and Adamczewski, the fourth paper, emphasizes the importance of investigating planetary atmospheres to gain insights into the origin, evolution, and processes influencing celestial bodies with atmospheres. The central focus is on the pivotal role of radiative transfer (RT) and its computational application in interpreting planetary spectra. With the continuous progress in observations, atmospheric modeling, and inference techniques, a variety of RT and parameters retrieval codes have emerged. The main challenge lies in choosing the most appropriate code for specific problems. To address this issue, the paper provides a comprehensive mini-overview of various RT and retrieval codes available in planetary science. The primary goal is to assist the (exo)planetary science community by presenting a clear and accessible list of codes, serving as a valuable resource for researchers and practitioners in the selection and application of these tools for planetary atmospheric studies and mission planning.

In the fifth paper, Limaye and Garvin discusses the current landscape and future prospects of Venus exploration, highlighting the development and planning of at least ten missions set to explore Venus in the next two decades, with a focus on atmospheric chemistry and surface/interior primary scientific goals, and past and present habitability objectives too. While previous missions

1 https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html.

predominantly relied on flight-tested platforms like orbiters and general atmospheric probes, the current planning does not include longer-lived atmospheric platforms or landers. The paper underlines that certain fundamental questions about Venus are likely to remain unanswered even after the upcoming wave of missions, set to commence in 2029 and extend through the 2030s. In a forward-looking approach, it outlines the major scientific questions that future Venus missions should address to advance our understanding of the planet as a complex system. The necessity for longer-lived atmospheric platforms, surface stations, and the eventual return of atmospheric and surface samples is highlighted. While concepts for such missions are in development for upcoming international opportunities, they await further technological investment to meet scientific and performance expectations and address longstanding science priorities.

In summary, these papers offer a partial snapshot of the state-of-the-art framework for the future of planetary exploration. They encompass approaches to overcoming mission challenges, developments in mission concepts, initiatives, and measures, *etc.*, providing valuable insights into the evolving landscape of planetary exploration.

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Conflict of interest

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