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Editorial: Exploring frontiers: astroparticle, space science and public health for future crewed space missions

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Editorial on the Research Topic
Exploring frontiers: astroparticle, space science and public health for future crewed space missions

Introduction

As humanity sets its sights on long-duration space travels and permanent outposts on the Moon and Mars to start a life beyond Earth, understanding the radiation-induced effects and underlying mechanisms has never been more critical. The Research Topic *Exploring frontiers: astroparticle, space science and public health for future crewed space missions* brings together pioneering studies that span various disciplines—from radiation biology and toxicology to neurophysiology and mental health. Collectively, these contributions aim to highlight the multifaceted risks of spaceflight and inform countermeasures to protect human health during future crewed missions.

Astronauts are exposed to complex and variable particle radiation in space, while microgravity-induced deconditioning, altered immune responses, and psychological stressors challenge human adaptability. This Research Topic of ten peer-reviewed articles reflects the growing synergy between space science, astroparticle physics, and public health in confronting these challenges with innovative methodologies and translational insights.

Radiation exposure and biological consequences

Radiation remains one of the most significant health threats in space. Several articles in this collection tackle its acute and chronic effects from biological and engineering perspectives. Cai et al. investigate how the gut microbiome could serve as a predictive biomarker for radiation-induced intestinal injury. It identifies Erysipelatoclostridium and its metabolite ptilosteroid A as potential indicators of intestinal damage. Leung et al. explore the late effects of heavy-ion radiation on immune cell function, specifically splenocyte subpopulations and NK cell cytotoxicity, providing insight into the long-term immunological risks astronauts may face.

In a translational leap, Daiz et al. also assessed the protective effects of curcumin-loaded nanolipoprotein particles (cNLPs) against acute gastrointestinal injury induced by radiation doses equivalent to those of a Mars mission. This study presents a potential countermeasure and highlights the importance of nanotechnology in the field of space radiation medicine.

On a molecular level, Raber et al. present an experimental analysis of the effects of 5-Ion (simplified GCR simulator) beam irradiation, both with and without hindlimb unloading, examining behavioral and metabolic shifts in a rodent model. This reinforces how mechanical unloading can exacerbate the systemic effects of radiation.

Countermeasures and physiological protection

Countermeasures are essential to mitigate the detrimental effects of prolonged microgravity. Arbeille et al. in this collection presents compelling data showing that exercise with artificial gravity, as well as exercise alone, can prevent morphological changes in organs and blood vessels during simulated microgravity (55 days of head-down tilt bed rest). These findings highlight the importance of integrated exercise protocols in maintaining astronaut health during extended missions.

Microgravity also has far-reaching effects on hormonal systems. Cutigni et al., in a narrative review on this topic, discuss how microgravity impairs endocrine signaling and reproductive health in women, emphasizing the need for sex-specific research and countermeasure development to ensure the health of all crew members on future missions.

Lunar dust and environmental toxicology

With renewed interest in lunar exploration, the environmental hazards of the Moon's surface are receiving renewed attention. Crucian et al. characterize pulmonary and systemic immune alterations in rats exposed to airborne lunar dust, while Colorado et al. assess the immunogenicity and allergenicity of lunar dust particles. These findings raise crucial safety considerations for astronauts engaging in extravehicular activities and long-term lunar habitation.

Measurement, modeling, and simulation

Understanding the radiation environment is foundational for mission planning. A key contribution in this area is a study presented by Chicco et al., which uses Bonner sphere spectrometry to measure high-energy neutron spectra from 1 GeV/u 56Fe ion beams and compares the results with Monte Carlo simulations. This work provides critical validation data for radiation transport models and shielding design.

Mental health and evolutionary medicine

Beyond the physiological aspects, the psychological dimensions of space travel demand equal attention. A novel article by Saniotis et al. in this collection advocates for an evolutionary medicine approach to mental health, arguing that the stressors of long-duration missions may evoke mismatches between our evolved biology and the artificial conditions of space. By addressing these mismatches, this work opens new avenues for mitigating psychological risks in space environments.

The role of interdisciplinary research in space exploration-related topics

Addressing the complexities of human spaceflight demands a deeply interdisciplinary research approach. The unique and multifaceted challenges presented by space environments—such as radiation, microgravity, confinement, and isolation—cannot be fully understood or mitigated within the boundaries of a single discipline. A systems-level perspective is essential, one that integrates knowledge from physics, chemistry, biology, medicine, engineering, and behavioral sciences.

For instance, understanding the effects of cosmic radiation involves astroparticle physics and radiation biology, as well as toxicology, microbiome research, and materials science for shielding solutions. Similarly, counteracting microgravity-induced deconditioning requires insights from physiology, biomechanics, exercise science, and even aerospace engineering to design effective countermeasures. Moreover, the psychological and social challenges of long-duration missions highlight the need for contributions from neuroscience, psychiatry, and human factors research. We can only anticipate interactions between physiological systems and environmental stressors by fostering active collaboration across these domains, developing robust predictive models, and creating effective interventions. As space missions extend in duration and distance, particularly toward the Moon, Mars, and beyond, the integration of disciplines becomes advantageous and imperative.

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Exploring Frontiers: Astroparticle, Space Science and Public Health for Future Crewed Space Missions

Strategic Domains	Focus Area	Key Research Threads
Radiation Effects	Heavy-Ion Radiation	Immune system modulation (splenocytes, NK function)
		Gut microbiome response (Erysipelatoclostridium, ptilosteroid A)
	SEP/GCR Radiation Exposure	Acute gastrointestinal injury
		Nanoparticle countermeasures (curcumin-loaded cNLPs)
	Ion Beam Exposure & Combined Stressors	Behavioral and metabolic alterations
		Hindlimb unloading as a compounding factor
Mental Health & Evolutionary Medicine	Psychological Stressors	Isolation, confinement, sensory monotony
		Evolutionary Mismatch
		Maladaptation to space environments
		Bioastronautics-informed approaches to reselience
	Endocrine & Reproductive Health	Hormonal disruption in microgravity
		Reproductive implications for women astronauts
Countermeasures & Physiology	Artificial Gravity & Exercise	Protection against vascular and organ morphological changes
		Mitigation of microgravity-induced deconditioning
	Endocrine & Reproductive Health	Hormonal disruption in microgravity
		Reproductive implications for women astronauts
Lunar & Environmental Hazards	Lunar Dust Exposure	Pulmonary and systemic immune effects
		Immunogenicity and allergenicity of regolith particles
Measurement & Simulation	Neutron Spectrometry	High-energy particle measurement
		Monte Carlo modeling validation
		Radiation environment characterization

FIGURE 1
Strategic Domains and Key Research Threads in the Research Topic Collection. This figure presents a structured, table-like representation of a conceptual mind map, outlining the main strategic domains and associated research threads addressed in the collection. It highlights the high degree of interdisciplinarity inherent in this field. It serves as both a synthesis of current research directions and a practical reference for stakeholders, including space agencies, research institutions, academia, and industry, who are committed to advancing knowledge for safe human deep space exploration and long-term habitation.

This Research Topic exemplifies how such integration leads to novel insights and tangible solutions, from nanotherapeutics and exercise protocols to evolutionary perspectives on mental health. Expanding interdisciplinary research activities is crucial for accelerating discovery, translating findings into practice, and safeguarding human health in space. Continued investment in cross-disciplinary platforms and collaborative frameworks will empower the scientific community to overcome existing knowledge gaps and prepare for space exploration's profound physiological and psychological demands. In doing so, we advance space science and catalyze innovations with applications on Earth, reinforcing the mutual benefits of research that transcends traditional boundaries. The diversity of scientific contributions in this Research Topic reflects the increasing convergence of multiple disciplines toward a unified understanding of the challenges associated with human spaceflight. As illustrated in Figure 1, the Research Topic's conceptual framework, presented as a mind map in a table-like format, summarizes the strategic domains and key research threads addressed across the collection. This structure not only demonstrates the wide-ranging interdisciplinary nature of the field but also serves as a practical guide for stakeholders aiming to support safe and sustainable human exploration beyond Earth.

Conclusion

Together, the articles in this Research Topic exhibit how multidisciplinary collaboration can help address one of the most significant challenges in human exploration. From microbial biomarkers and nanotherapeutics to lunar toxicology and psychological resilience, these studies collectively push the frontiers of knowledge required for the next giant leap.

This Research Topic grounds public health within the framework of astroparticle physics and space science, informing the design of

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safer, more effective crewed missions. It enriches our understanding of human biology under extreme conditions. We hope this Research Topic serves as a springboard for future studies and stimulates continued cross-disciplinary dialogue as we prepare for a multi-planetary future.

Author contributions

AB: Writing – review and editing, Writing – original draft. GC: Writing – review and editing. CC: Writing – review and editing. ND: Writing – review and editing. CP: Writing – review and editing. FT: Writing – review and editing. LS: Writing – review and editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.