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Rheology beyond Earth

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I. INTRODUCTION

Why do humans go to space?—Space fascinates humankind, as echoed in countless works of fiction. Leaving the familiar environment of Earth requires rethinking our most basic assumptions and interrogating the physics that lies beneath our everyday intuition. In this need for understanding underlying mechanisms, space and rheology come together. Nearly 100 years after Fritz Lang, in his silent movie "*Frau im Mond*" ("The Woman in the Moon"), imagined how fluids flow in low gravity, at the time of a new *space rush* that shall bring the first woman to the Moon, we return to the questions of what rheology becomes beyond Earth, and why it matters (Fig. 1).

The quest to understand how materials deform and flow transcends disciplinary boundaries—and so does the effort to explore space. Confronting the harsh, challenging, and often uncertain conditions of space is inherently multidisciplinary, combining the physical and life sciences and engineering all the way to sociology, anthropology and design. Such space research includes many areas of interest to the rheology community. Exploration-driven research supports efforts to understand the properties and history (and perhaps habitability) of space bodies. Microgravity and hypergravity research focuses on unveiling the effect of gravity on matter and phenomena, uncovering interactions otherwise hidden, and allows new phenomenology to emerge. We can use research on the effect of altered gravity, not only for understanding how materials and processes change when traveling through space but also to enable testing theories in parameter regimes otherwise inaccessible.

FIG. 1. Earthrise taken by Apollo 8 crew member Bill Anders on Christmas Eve, 1968 (Credit: NASA; image ID: 68-HC-870).

This special issue, inspired by the remarkable interest and lively discussions at the 95th Annual Meeting of the SoR in 2024 (Austin, Texas), showcases the breadth and momentum of rheological research in altered gravity.[1] The response to the session was overwhelming, and we are happy to report that the next International Congress on Rheology (Guangzhou, China, in 2027) will also feature a space-related session, for the first time in its history. The quality and diversity of the work submitted to this issue reflects that energy. Across the papers you will find in this issue, themes emerge that outline the rapidly growing landscape of space applications and altered-gravity research.

II. A PANORAMA OF RHEOLOGY RESEARCH IN SPACE APPLICATIONS AND LOW-GRAVITY RESEARCH

Specifically important for space exploration, **granular materials** are critically sensitive to gravity, as the latter easily competes with the forces that cause deformation and flow. Hence, gravity shapes granular flows profoundly, and granular rheology emerges as a central theme in this issue. Granular rheology in altered gravity has the twofold aim of predicting how powders will behave in space and improving our understanding of how they flow on Earth. One effect of reduced gravity is to make other forces between the particles more relevant, which enables exploring granular dynamics

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[1]A review of this symposium can be found in the Rheology Bulletin vol. 94(1), August 2025.

that rely less on gravity. An example of this is reported in this special issue; Stumpf *et al.* [1] combine flow down an incline (to effectively vary gravity) with large-amplitude oscillatory shear to unveil the different flow regimes. Gravity acts in granular flows to induce secondary flow fields, and thus, the behavior near jamming can be critically altered in microgravity. Using a drop tower as a ground-based low-gravity research facility, D'Angelo *et al.* [2] demonstrate that jamming occurs at lower packing densities and that granular matter exhibits higher viscosity in microgravity than in Earth's gravity; this has strong implications for the extraterrestrial handling of granular materials, and for understanding powders on ground. Turning to simulations, the effect of gravity on granular flow is studied with the aim of determining the relevant dimensionless numbers that scale gravitational against other forces. A specific, highly relevant application for planetary science is the behavior of particles impacting a granular bed: Miklavcic *et al.* [3] show that when initial velocities are scaled with the Froude number, impact trajectories in cohesionless granular media collapse across different gravitational conditions. Tadlock *et al.* [4] simulate quasi-2D silo discharge under varying gravity and particle stiffness, and show that the flow rate exhibits significant deviations from the classical scaling: either slower or faster than predicted, depending on outlet size to particle diameter ratio and on a stiffness-to-gravity ratio. Mesoscopic-scale analysis reveals that these deviations are strongly fluctuation-dependent and best correlated with granular temperature.

Extraterrestrial sand or **regolith** is the material that covers the surfaces of the Moon, Mars, or small celestial bodies; it represents a class of challenging and interesting granular materials. Regolith, and what can be derived from it at low (energetic) cost, will be the extraterrestrial building material of choice. In such ***in situ* resource utilization** applications, the material must first be transported before being processed: Studies on the flow of regolith simulants through orifices and hoppers highlight the complex, gravity-dependent nature of its discharge behavior. Lunar regolith simulants, terrestrial mimics of Moon materials, are used in investigations of the most effective modes of conveying materials through hoppers, aided by vibration, as investigated by McKenzie *et al.* [5] and Lappa *et al.* [6]. Rheology also plays an important role in addressing how such building materials can be processed and formed once activated, for example, for the aluminosilicate geopolymer binders studied by Egnaczyk and Wagner [7], which are shown to function in the harsh conditions of low Earth orbit (LEO) using NASA's MISSE-FF[2] test station outside the International Space Station (ISS).

There is already a long history of microgravity research related to **soft matter and suspensions.** Scientific research facilities aboard the ISS, in particular, have enabled a broad range of research, as highlighted by Martinelli *et al.* in the review of the European Space Agency (ESA) sponsored experiments [8]. Hasanova *et al.* [9] explore the Soret effect for particles in suspension, e.g., thermophoresis, which is revealed in microgravity conditions aboard the ISS. The ISS also provides opportunities for studying the effects of forces acting between particles in suspension that drive self-assembly, which are otherwise convoluted by gravity, as demonstrated by Conradt and Furst [10]: Their microgravity research on magnetic colloids explores a handle for parameter tuning of dynamic magnetic fields to drive self-assembly of structures that cannot be achieved readily under Earth's gravity.

Classical fluid dynamics is also represented in this issue. Gravity alters phase separation phenomena, owing to the different density of the phases. It is always worth recalling just how many applications rely on, or are affected by, the gravitation mixing or demixing of fluids—including multiphase flows as well as many mass transfer operations such as distillation, as well as separation by sedimentation and creaming, typical in industrial processes (e.g., emulsification, crystallization, foaming, etc.). Computer simulations of vapor-liquid phase separation by Lamura [11] reveal that the power law exponents characterizing the growth of phase-separated fluid domains increase with gravity. Heitmeier *et al.* [12] show another intriguing example: droplet spreading of yield-stress fluids, where a change in gravity alters the force balance between competing effects of interfacial and yield-stress, thus testing analytical scaling laws in regimes that cannot be explored under Earth gravity.

Moving beyond soft materials and suspensions, microgravity effects on **biological systems** can manifest in rheological phenomena. Changes in intercellular viscosity affect human physiology and are implicated in adverse symptoms experienced by astronauts during flight. In preparation for upcoming microgravity experiments, van Rijthoven *et al.*'s pilot study of single particle tracking microrheology in hypergravity demonstrates the methodology and shows early indicators of gravitational effects [13]. The intriguing observation that gravity influences how bacteria organize in biofilms is of technical importance for the design and maintenance of life support systems in human space exploration. Marra and Caserta provide a perspective on how biofilm rheology is central to understanding biofilm structure and development and further the significant effects of gravity [14]. Such quantitative understanding is necessary for spacecraft hygiene and life support reliability but also better informs strategies for mitigating undesired biofilm formation across a wide spectrum of terrestrial applications affecting human health.

III. WITH A GREAT LABORATORY COMES GREAT RESPONSIBILITY

As demonstrated by the cross section of space-related research featured in this special issue, *space applications and low-gravity research* are not just about going to space: It is equally about using new tools, including altering gravity, **to improve life here on Earth**. Numerous scientific advances in the modern *space age* have been enabled by existing gravity-altering platforms in low Earth orbit, including the ISS, the Tiangong Space Station (天宫空间站) and orbital

[2]The Materials ISS Experiment Flight Facility (MISSE-FF) is a commercially available orbital research platform mounted outside the International Space Station, enabling researchers to test concepts in the extreme environment of space.

satellites, as well as suborbital sounding rockets, parabolic flights, drop towers, and centrifuges worldwide. These facilities have opened unprecedented opportunities to study matter beyond the Earth's gravity. We strongly advocate for the continued development of new, advanced scientific laboratories currently under discussion, on Earth and in LEO, but also *cis*-lunar orbit and perhaps even on the lunar surface.

This viewpoint emphasizes the role of research on altered gravity, including rheology, as a driver of innovation, helping Earth inhabitants to benefit from space. The big dream of *colonizing* space might be an illustrious igniter of inspiration for some, but as shown in this compendium, the associated symposium, and the broader literature, the research done using ground-based platforms and LEO has immediate, tangible applications here on Earth, shaping technologies and solutions we rely on today, e.g., protein crystallization, improvements in semiconductor processing and solar cells, water purification and air filtration systems, fire safety, firefighting foams, as well as improving our understanding of human physiology.

As co-editors of this compendium, we are continually inspired by the ability of space research to transcend disciplinary boundaries, challenge our physical intuition, and reshape how we understand matter—both on Earth and beyond. The environment of space, even in LEO, is still harsh, and it challenges researchers to think sustainably and maximize resilience—a set of traits that we urgently need, not just for building habitats in space but also to maintain *the friendliest habitat we know*—Earth. Going to space is plunging in an environment where everything we take for granted is questioned. Earth gravity and atmosphere of course; but also the caress of a breeze, the smell of wet grass in the morning dew, and sunlight warming our skin: Earth-bound experiences we take for granted. The *Earthrise* photo from Apollo 8[3] or the *Pale Blue Dot* images returned from Voyager 1[4] remind us of the fragility and preciousness of our Earth, motivating the effective use of space research to improve the human condition both on and off planet.

As access to space expands, so does our responsibility to ensure its knowledge serves all of humanity. Low gravity research must remain a *scientific common,* shaping infrastructure, health, ecology: It is a driver of innovation, too transformative, too fertile to be appropriated. In the words of John F. Kennedy: *"We set sail on this new sea because there is new knowledge to be gained and new rights to be won and they must be won and used for the progress of all [hu]mankind."*

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

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