Appendix

Significance of this work

Studying MO convection is crucial for understanding the early stages of planetary formation and differentiation. The convection within this molten layer drives the separation of materials, leading to the formation of a dense core, mantle, and crust, which influences the planet's geological structure and composition. This process also plays a significant role in the planet's thermal evolution, determining the cooling rate and heat distribution within its interior. Our work will help us understand the crystallization process in depth, as well as the formation of the crust at the surface. The convection in the MO can lead to volcanic activity and tectonic processes, which continue to shape the planet's surface. In this research, we will produce the first 3D combined global model of dynamo action and degassing on primordial Earth. The dynamo effect within the core helps generate a magnetic field, which is vital for protecting the planet from harmful solar radiation. Understanding these convection processes also provides insights into the habitability of exoplanets by influencing surface temperatures and conditions that may allow liquid water to exist. Furthermore, MO convection provides valuable clues about the conditions in the early solar system, as well as the potential for life on other planets.

Quantifying volatile outgassing and its subsequent escape from an Archean terrestrial MO is crucial for understanding the evolution of primordial planetary atmospheres. The outflowing material plays a vital role in sculpting the atmosphere over geological timescales—an evolution that depends on the incoming stellar flux and the presence or absence of an intrinsic planetary magnetic field. Furthermore, escape from planetary atmospheres is an essential indicator in determining their habitability potential, alongside their interior composition and orbital features. Extrasolar planets exist under a broader range of physical conditions than those found in our solar system. Therefore, it is important to understand planetary atmosphere formation mechanisms across a broad range of stellar environments if we are to assess their habitability. Our proposed project also investigates how variations in the interior rheologies of exoplanets contribute to tidal decay and the resulting observable signatures, helping us better understand their evolutionary pathways.

Relevance to NASA Planetary Science Research Program goals

The proposed work aims to elucidate a fundamental planetary process using both analytical and computational models. According to Chapter 2 of the 2023 NASA Science Plan [1], exoplanet science occupies a unique niche between the Astrophysics and Planetary Science Divisions. We believe this study is more aligned with the Planetary Science Division (PSD) for several reasons. First, the PSD's main focus is understanding the formation and early evolution of planetary systems. The processes of magma ocean evolution and convective outgassing are critical in the early stages of planetary development and have impacted both exoplanetary populations and the Solar System, directly relating to the PSD's primary goals. Furthermore, the PSD is dedicated to fundamental research that is essential for evaluating planetary habitability and planet interior dynamics play a significant role in determining the conditions for habitability. As such, this project is relevant to both the exoplanetary and Solar System goals of the PSD.

This work addresses several high-priority science questions from the most recent Planetary Science Decadal Survey [1, 2], particularly in the following themes: *Theme: Solid Body Interiors and Surfaces (Question 5)* includes Q5.2: "How Have the Interiors of Solid Bodies Evolved?", Q5.3: "How Have Surface/Near-Surface Characteristics and Compositions of Solid Bodies Been Modified by, and Recorded in, Interior Processes?", Q5.4: "How Have Surface Characteristics and Compositions of Solid Bodies Been Modified by, and Recorded in, Surface Processes and Atmospheric Interactions?", and Q5.6: "What Drives Active Processes Occurring in the Interiors and on the Surfaces of Solid Bodies?", *Theme: Solid Body Atmospheres, Exospheres, Magnetospheres, and Climate Evolution (Question 6)* includes Q6.1: "How Do Solid Body Atmospheres Form, and What Was Their State During and Shortly After Accretion?", Q6.4: "How Do Planetary Surfaces and Interiors Influence and Interact with Their Host Atmospheres?", and Q6.5: "What Processes Govern Atmospheric Loss to Space?", *Theme: Insights from Terrestrial Life (Question 9)* includes Q9.3: "How Do Investigations of Earth's Subsurface Environments Inform What Habitability and/or Life on Other Worlds Might Look Like?", *Theme: Exoplanets (Question 12)* includes Q12.5: "Solid Body Interiors and Surfaces." Furthermore, magma ocean dynamics and evolution have been identified as key science requirements by NASA in planning for future astronomy/exoplanet missions, as well as past lander missions to Mars, including InSight and Perseverance, to study its interior [2].

	Science Questions	Tasks	Products	’25	’26			’27			’28
				F	SP	SM	F	SP	SM	F	SP
GOAL – 1	How does planetary rotation affect the entrainment rate, mixing efficiency, and convective energy in the MO?	Generate convective mixing and vorticity maps	a) 3D spherical simulations vs. Ro								
		Determine the angular dependence of heat and K.E. flux	b) Profiles of convective composition								
	How was the early terrestrial magnetic field created?	Model the magnetic field in the mantle	Magnetic field model of the Archean MO								
		Validate results with PINT data									
	Paper on rotating magma convection in Archean MO										
GOAL – 2	How did turbulent fluid flow in early Earth magma ocean governed convective outgassing?	Combine our 3D MO model with radiative-convective atmospheric model	Feedback-based model of early Earth volatile outgassing								
		Study early Earth MO evolution with a volatile atmosphere									
	Paper on convective degassing from early Earth MO										
GOAL – 3	How does rheology-induced tidal heating impact the MO of super-Earths?	Develop a theoretical model of the tidal deformation	Rheology-driven tidal heating model								
		Compare the diurnal variations with the observed phase curve									
	How does tidal bulge affect the spin–orbit misalignment?	Study the response of MO to obliquity tide	Obliquity tide model for super-Earths								
		Assess the results against spin–orbit misalignment data									
	Paper on MO-induced tides in super-Earths										

Table A1: **Research questions, tasks, and products.** For each task, we reserved one month for contingency at the end of the proposal period, resulting in a cumulative contingency period of five months. F = Fall, SP = Spring, SM = Summer.

References

[1] National Academies of Sciences, and Medicine, Engineering. *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*. The National Academies Press, 2023. DOI: 10.17226/26522. URL: https://ui.adsabs.harvard.edu/abs/2023owld.book.....N.

[2] National Academies of Sciences, and Medicine, Engineering. *Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade*. The National Academies Press, 2023. DOI: 10.17226/27209. URL: https://ui.adsabs.harvard.edu/abs/2023owlp.book.....N.