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Eco-Astronomy and Paleontology: Investigating Earth's Harbored Life Through Interdisciplinary Perspectives – Insights from Sri Lanka

Aravinda Ravibhanu Sumanarathna

Department of Research and Innovations, Eco Astronomy Inc.

ABSTRCT

Eco Astronomy, a pioneering scientific discipline formally established in 2012 and articulated in 2016 at the Royal Asiatic Society of Sri Lanka, represents a transformative convergence of Astrobiology, paleontology, and petrology. This interdisciplinary framework seeks to elucidate the fundamental prerequisites for life in extreme environments, both terrestrial and extraterrestrial, by synthesizing paleontological and mineralogical data from Earth and other planetary systems. Central to this inquiry is the examination of habitability determinants—such as temperature, water availability, radiation shielding, sunlight, and oxygen levels—with a particular emphasis on planets orbiting G2-type stars, analogous to our Sun. Earth's mineralogical evolution, driven by solar energy over 4.6 billion years, provides a foundational benchmark for comparative planetary studies. Eco Astronomy leverages fossil records from biodiverse regions, including Sri Lanka, Argentina, and the USA, spanning the Jurassic, Miocene, and Quaternary periods, to reconstruct ancient environmental conditions and evaluate their implications for planetary habitability. A key objective is the development of a comparative model that juxtaposes terrestrial fossil data with extraterrestrial geological traces, such as those from Mars, to unravel the intricate relationships between fossils, minerals, and life-sustaining conditions. Through the analysis of these interdisciplinary datasets, Eco Astronomy advances our understanding of life's evolutionary trajectory, the potential for habitable environments beyond Earth, and the broader astrobiological implications for life in the universe. This research underscores the critical role of ongoing investigations in deciphering the complex dynamics of planetary habitability and the search for extraterrestrial life, offering profound insights into the universal principles governing the emergence and sustainability of life.

Article information | Key Words: Eco Astronomy, Astrobiology, Paleontology, Fossils, Extreme condition, Sri Lanka.

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Corresponding Author: Aravinda Ravibhanu | email: aravinda.ecoastronomy@gmail.com

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INTRODCUTION

Astronomy has long stood as a cornerstone of scientific advancement, driving humanity's understanding of the cosmos and our place within it. From the earliest observations of celestial bodies to the modern era of large-scale observatories, space missions, and artificial satellites, the field has continually expanded the frontiers of knowledge. However, this progress has come with growing environmental costs, as the construction, launch, and operation of these technologies contribute to ecological degradation. In response, the concept of *eco-astronomy* has emerged as a transformative paradigm, seeking to reconcile the pursuit of astronomical discovery with the imperative of ecological sustainability (Sumanarathna et al., 2016).

At the heart of astronomical inquiry lies the profound question of whether life exists beyond Earth—a question that has captivated scientists and the public alike for centuries. This quest has given rise to *Eco Astronomy*, an interdisciplinary field that bridges astrobiology, paleontology, and planetary science. Eco Astronomy, formally introduced in 2012 and further developed in subsequent publications (Author et al., 2016), represents a novel approach to understanding the conditions necessary for life to emerge and thrive, both on Earth and on other planetary bodies. By integrating paleontological and geological data, this discipline provides a framework for identifying habitable environments elsewhere in the universe.

Central to Eco Astronomy is the study of Earth's geological and paleontological records, which serve as a critical archive of past environmental conditions and biological evolution. Fossil records, in particular, offer invaluable insights into the interplay between life and its planetary environment. Regions such as Sri Lanka, with their diverse fossil assemblages and geological complexity, provide unique analogs for investigating extraterrestrial habitats. For instance, Sri Lanka's rich fossil records and mineralogical diversity have been leveraged to develop comparative models for assessing planetary habitability, with a particular focus on Mars—a prime candidate for past life due to its geological and hydrological history (Sumanarathna et al., 2016).

The interdisciplinary nature of Eco Astronomy underscores its potential to address fundamental questions in astrobiology. By examining Earth's mineralogical and biological evolution, researchers can extrapolate principles that may apply to other planetary bodies. This approach not only advances our understanding of life's origins and resilience but also informs the design of future space missions aimed at detecting biosignatures on planets such as Mars. As the field continues to evolve, it promises to deepen our appreciation of the delicate balance between scientific exploration and environmental stewardship, ensuring that humanity's quest for knowledge remains sustainable for generations to come.

As humanity ventures into the exploration of novel interdisciplinary concepts such as *Eco Astronomy*—a field that seeks to understand the relationship between astronomical phenomena and Earth's ecological systems—it becomes imperative to ground such inquiries in foundational scientific disciplines. Among these, paleontology emerges as a critical field of study, offering profound insights into the history of life on Earth and the processes that have shaped it over millions of years. Paleontology, the study of ancient life through the examination of fossils, is not merely a historical science but a discipline of immense relevance to the modern and future world. By analyzing the fossil record, we can decipher how past climate changes have influenced the evolution and extinction of organisms, as well as how life itself has altered the physical environment (Benton, 2003; Jablonski, 2005). These insights are invaluable for understanding the principles of extinction, evolutionary dynamics, and biodiversity, all of which are crucial for predicting and mitigating the impacts of contemporary global challenges.

One of the most pressing applications of paleontology lies in its ability to illuminate the effects of climate change on ecosystems. By studying how past climatic shifts have driven evolutionary adaptations and extinctions, we can better anticipate potential changes in future ecosystems and their implications for human land-use practices (Barnosky et al., 2012). Moreover, the fossil record provides a stark reminder of how exponential population growth and anthropogenic activities, such as urbanization and habitat destruction, mirror the environmental changes observed in Earth's deep history (Ellis et al., 2013). This parallel is particularly alarming given that human society and its political leaders have yet to fully confront the demographic realities of exponential population growth and its cascading effects on planetary ecosystems (Ehrlich & Ehrlich, 2013).

Paleontology also offers a unique temporal perspective, revealing the depth of Earth's history over millions of years. This long-term view fosters an ethic of planetary stewardship, emphasizing the need for sustainable practices to ensure the wellness of Earth's biosphere (Sepkoski, 2012). In the context of *Eco Astronomy*, this ethic becomes even more significant, as it underscores the interconnectedness of Earth's ecological systems with broader cosmic processes. By integrating the lessons of paleontology with the emerging field of *Eco Astronomy*, we can develop a more holistic understanding of the forces that shape life on Earth and beyond, ultimately guiding humanity toward a more sustainable and informed future.

Eco Astronomy, a specialized discipline within the broader field of Astrobiology, focuses on the study of exoplanetary materials and their preservation niches to gain insights into the potential for life beyond Earth. This emerging field is deeply rooted in addressing the fundamental questions that have driven Astrobiology: *What is life? Where can it be found?* and *how can we detect its signs?* These questions remain central to the field, as the concept of "life" itself is still open to interpretation and far from achieving a scientific consensus (Des Marais et al., 2008; Cockell et al., 2016). In the absence of a unified definition, the pragmatic approach of Eco Astronomy relies on identifying biosignatures—indicators of life as we know it—through comparative analyses and analogies with terrestrial life and its preservation.

The question of *where to search for life* is guided by feasibility and the principles of planetary habitability. Mars, our neighboring planet, emerges as a prime candidate due to its geological and environmental similarities to early Earth. During the Noachian period (~4.1–3.7 billion years ago), Mars exhibited conditions analogous to those of Earth's Hadean-Archaean eon (~4–2.5 billion years ago), including the presence of liquid water and a dense atmosphere (Carr & Head, 2010; Ehlmann et al., 2011). These conditions are thought to have provided the necessary free energy and chemical gradients for the emergence and sustenance of life. While Mars has since lost much of its surface water and atmosphere, its ancient rocks and sediments may still preserve fossil biosignatures, offering a window into its potentially habitable past (Grotzinger et al., 2014).

Beyond Mars, the discovery of exoplanets and the exploration of moons such as Europa (Jupiter) and Enceladus (Saturn) have expanded the scope of astrobiological research. These celestial bodies, with their subsurface oceans and potential for hydrothermal activity, represent promising targets for the search for life (Hand et al., 2009; McKay et al., 2014). The third question—*how to search for life*—requires a multidisciplinary approach, integrating techniques from geology, paleontology, and geochemistry. Earth's geological record serves as a critical analog for developing and testing methods to detect biosignatures on other worlds. Techniques such as Raman spectroscopy and X-ray fluorescence (XRF), employed in missions like the Mars Science Laboratory (2011) and Mars 2020, have proven effective in identifying biogenic elements, mineral phases, and organic compounds (Ming et al., 2014). These methods, refined through terrestrial studies, provide a foundation for interpreting data from extraterrestrial environments.

Paleontology, in particular, plays a pivotal role in advancing Eco Astronomy. Paleontologists bring a unique perspective on the processes that lead to the preservation of life's traces over geological timescales. Studies in paleobiology, fossil diagenesis, and geobiology contribute to the identification and validation of biosignatures, the characterization of organic matter, and the recognition of biominerals (Knoll et al., 2012; Westall et al., 2015). These insights are invaluable for interpreting data from Martian missions, such as those conducted by the Perseverance rover, and for building comparative databases that enhance our understanding of potential extraterrestrial life.

The integration of paleontological and geoscientific domains—including geobiology, geochemistry, and mineralogy—into astrobiology fosters a more unified approach to recognizing the epiphenomena of living systems. By leveraging Earth's geological record and refining analytical techniques, we can improve the chances of detecting life on other worlds and advance our understanding of life's origins and distribution in the universe (Summons et al., 2008; Steele et al., 2016). Eco Astronomy, therefore, represents a transformative direction in astrobiological research, bridging the gap between planetary science and the search for life in the cosmos.

METHOD.

The scientific method, deeply rooted in the interdisciplinary framework of Eco Astronomy and bolstered by a comparative analytical approach, represents a robust paradigm for exploring the potential for habitability beyond Earth. This methodology entails a meticulous examination of Earth's fossil records and mineralogical data, which serve as proxies for deciphering environmental conditions that may foster life on other celestial bodies. By focusing on regions of exceptional geo- and biodiversity, such as Sri Lanka, Argentina, and the USA, researchers can extract critical insights from fossil records spanning key geological epochs, including the Jurassic, Miocene, and Quaternary periods. These records provide a window into historical climatic conditions, flora, and fauna, offering a terrestrial baseline for comparative planetary science.

The integration of terrestrial data with geological observations from Mars, obtained through rover missions and satellite imagery, enables the identification of parallels and divergences in habitable conditions across planetary systems. Central to this investigation are key fossil and mineralogical specimens, such as the *Kuphus* fossil, Coprinisphaeridae ichnofossils, and Moqui marbles, which are analyzed to elucidate Exo-niche environments. Notably, the formation of hematite-rich spherules, colloquially termed "blueberries," observed by the Opportunity rover on Mars, is compared to analogous terrestrial processes to infer potential biosignatures and habitable conditions.

Petrological studies are employed to trace the fossilization pathways of these materials, while mineralogical analyses of fossil-bearing strata reveal the intricate interplay between biotic and abiotic factors in shaping habitable environments. By scrutinizing rock formations and their mineral compositions, this approach establishes connections between Earth's geological history and extraterrestrial landscapes, leveraging Martian data to identify potential biosignatures and habitable zones. Guided by the principles of Eco Astronomy, which emphasize the interconnectedness of planetary systems and their environmental histories, this integrated methodology advances our understanding of extraterrestrial habitability, paving the way for future astrobiological exploration and the search for life beyond our planet.

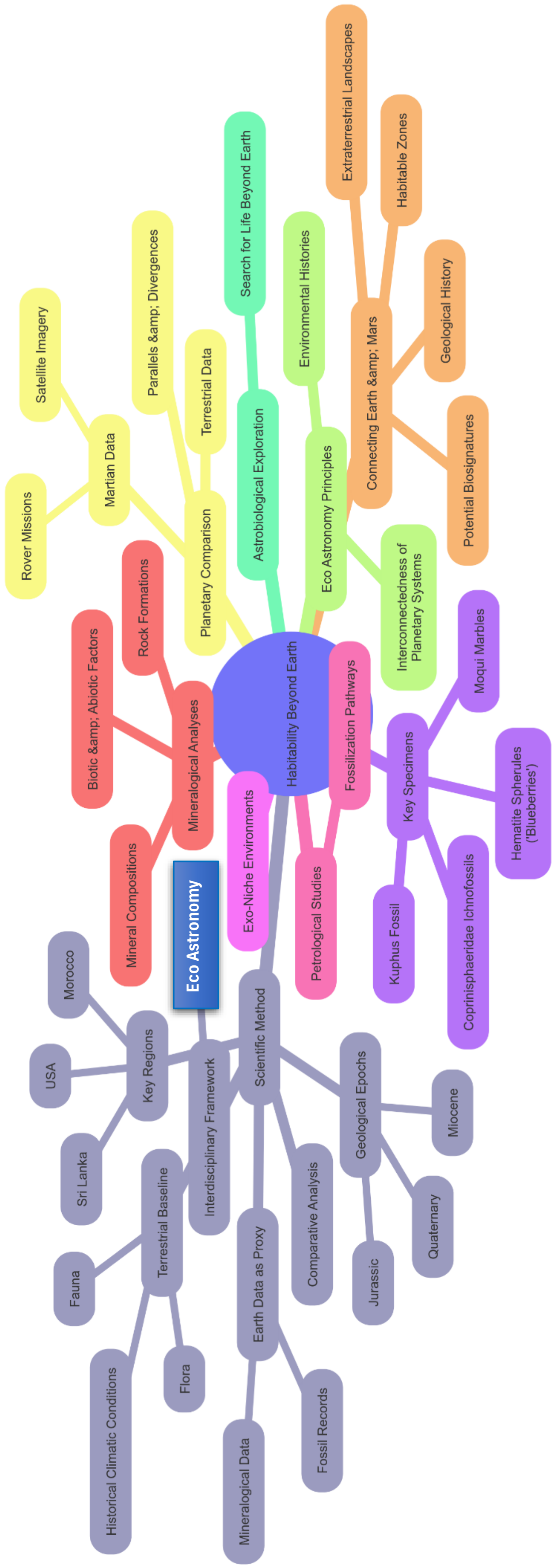

Figure 01: The quest to understand planetary habitability and the potential for extraterrestrial life has long been a cornerstone of astrobiological research. In this context, the Eco Astronomy Model emerges as a scientifically robust framework for exploring the conditions under which planetary environments can sustain and harbor life. This model is fundamentally rooted in the principles of harbor preservation and the intricate interplay of mineralogical processes, which collectively shape the dynamic systems capable of supporting life.

By focusing on geological-based sources, the Eco Astronomy Model provides a structured approach to deciphering the complex interactions between planetary surfaces, subsurface environments, and the potential for life-sustaining niches. Through the systematic analysis of key parameters—such as mineral composition, geochemical cycles, and environmental stability—this model offers a pathway to understanding the delicate balance required for the emergence and persistence of habitable conditions. As such, the Eco Astronomy Model not only advances our comprehension of planetary habitability but also serves as a critical tool for identifying and characterizing environments that may harbor life beyond Earth.

RESULTS

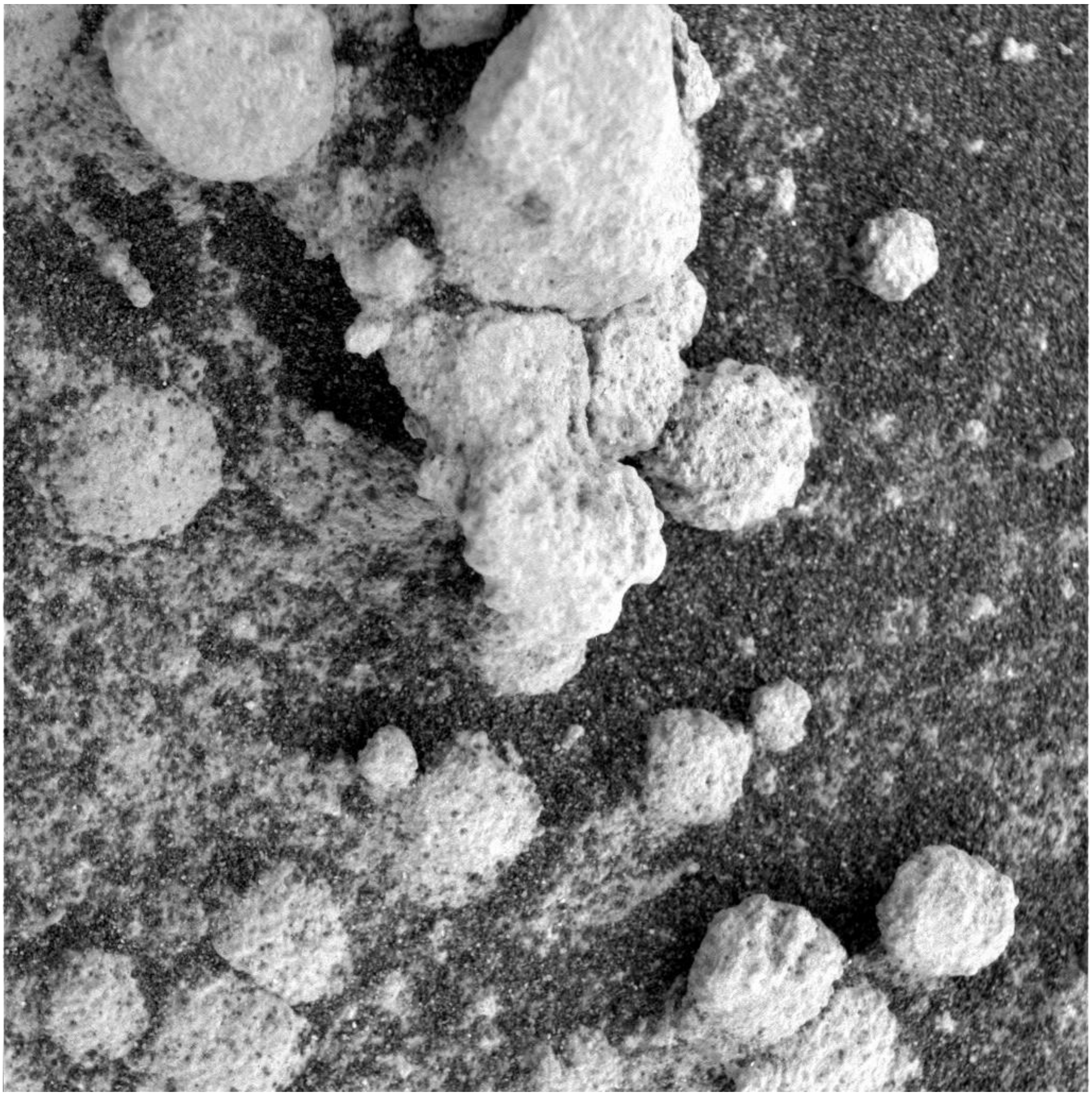

Figure 02: Image Code: 1M145849586EFF3505P2977M2M1 | This image presents a detailed microscopic view of errored spherules captured at Meridiani Planum, a region of significant scientific interest on Mars.

The photograph was obtained using the Instrument Deployment Device (IDD) aboard NASA's Mars Exploration Rover *Opportunity*. These spherules, characterized by their unique morphology and surface irregularities, provide valuable insights into the geological and environmental processes that have shaped the Martian landscape.

The presence of such features suggests potential interactions with water or other weathering agents in the planet's history. The *Opportunity* rover's advanced imaging capabilities have enabled researchers to study these formations at an unprecedented scale, contributing to our understanding of Mars past habitability and geological evolution.

This image underscores the importance of continued exploration and analysis of Martian surface materials, as each discovery brings us closer to unraveling the mysteries of the Red Planet.

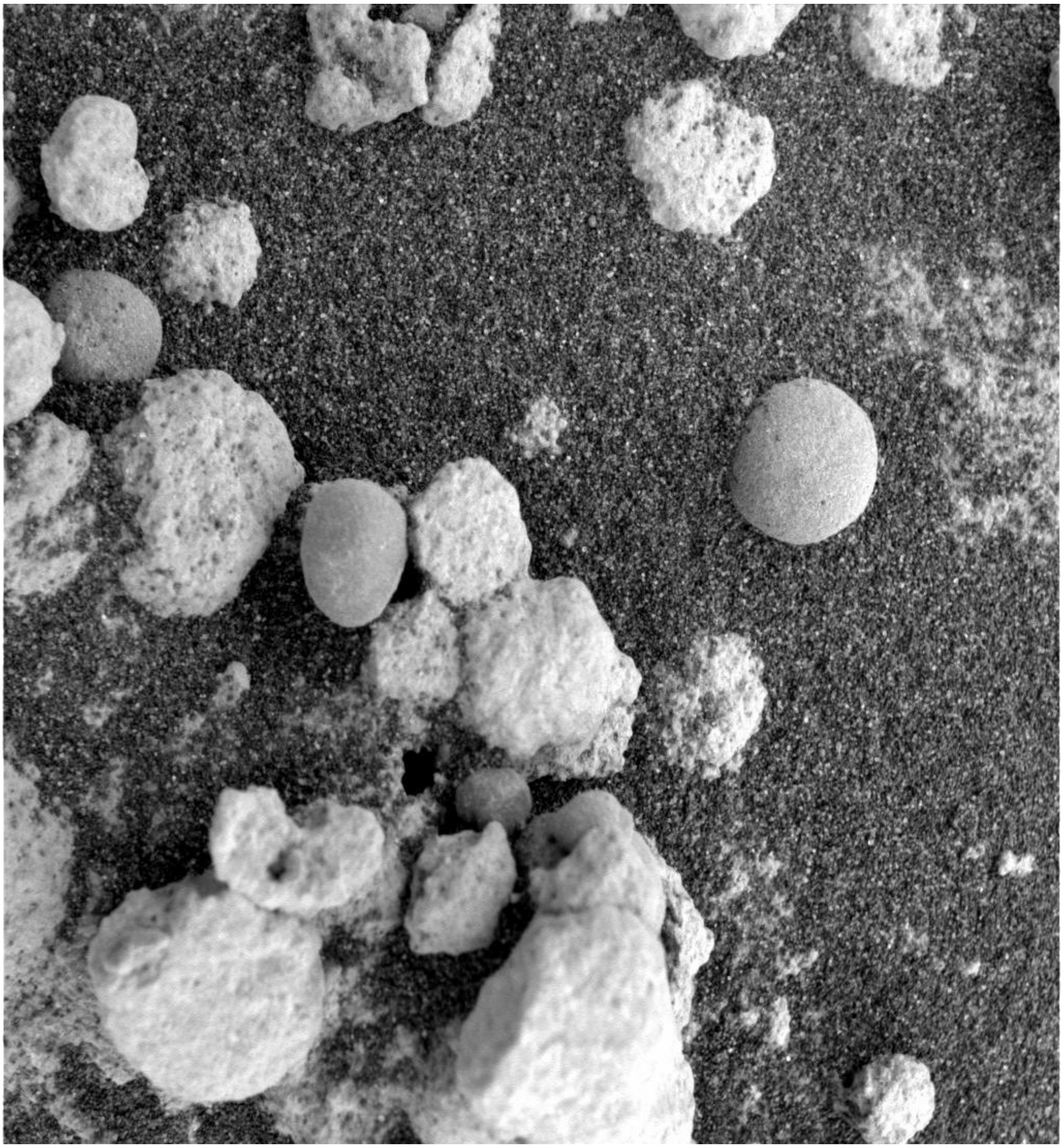

Figure 03: Image Code: 1M145849709EFF3505P2976M2M1| Stunning view of errored spherules and hematite balls at Meridiani Planum, Mars, captured by the Mars Exploration Rover Opportunity. The image also reveals a micro hydrothermal vent chimney, offering a glimpse into the planet's fascinating geological history.

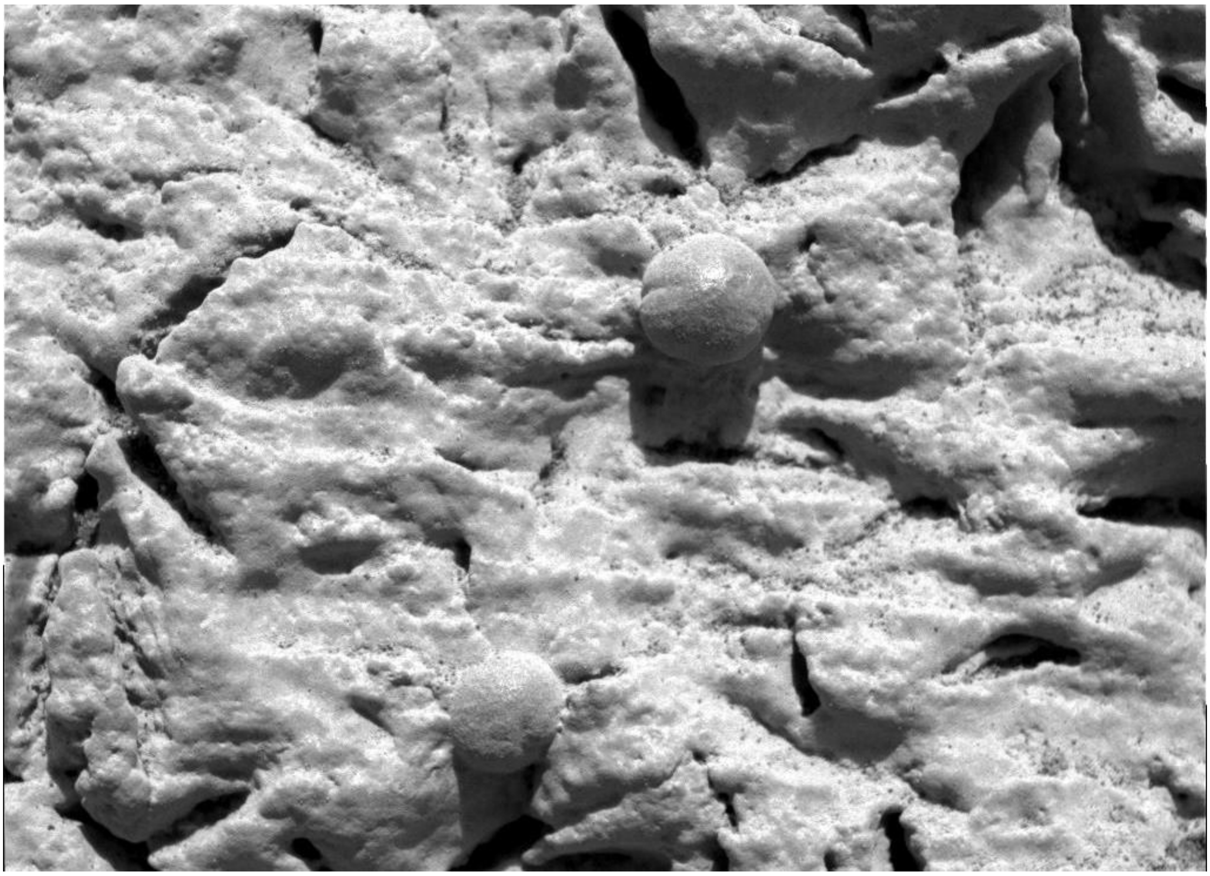

Figure 04: Close-up imagery of this matrix reveals the presence of embedded spherules. The image, covering an approximate 32 mm x 32 mm area, was captured on Sol 29 (2004-02-24) by the Mars Exploration Rover Opportunity.

Figure 05: These spherical [Moqui marbles] concretions are found primarily in the deserts of the American Southwest, particularly in Utah and Arizona. They're composed of iron oxide and sandstone, formationa is sismsisler to the hematite spherule on Mars. Image: Pspechtenhauser 2008.

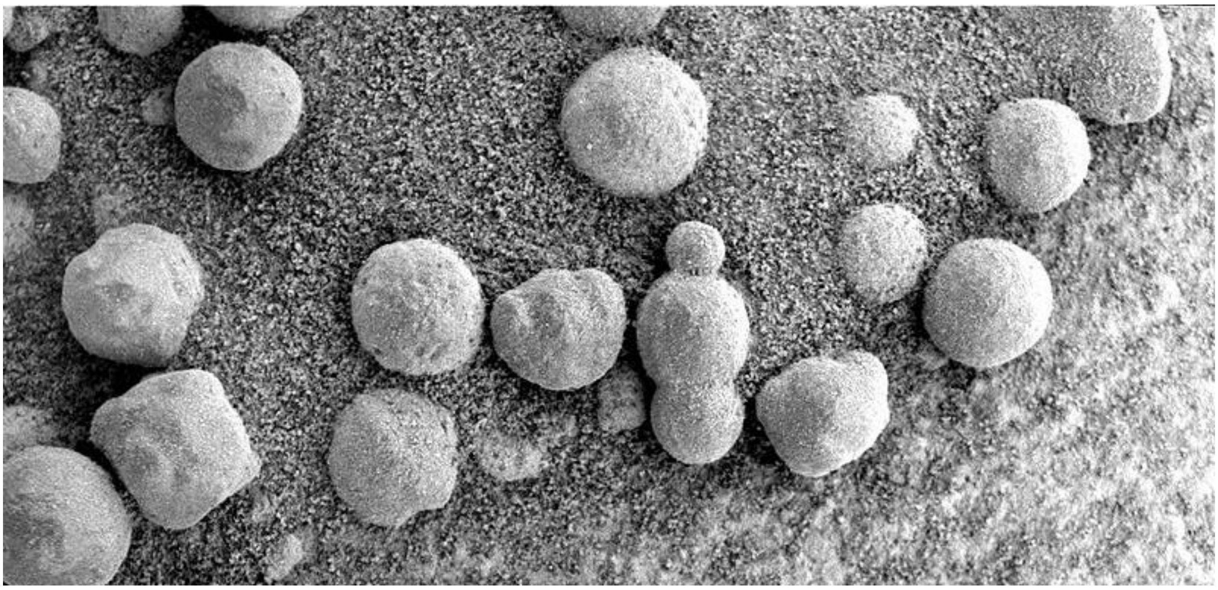

Figure 06: Image Code: 1M132266947EFF05AMP2987M2M1| Combined hematite spherules captured by Rover Opportunity.

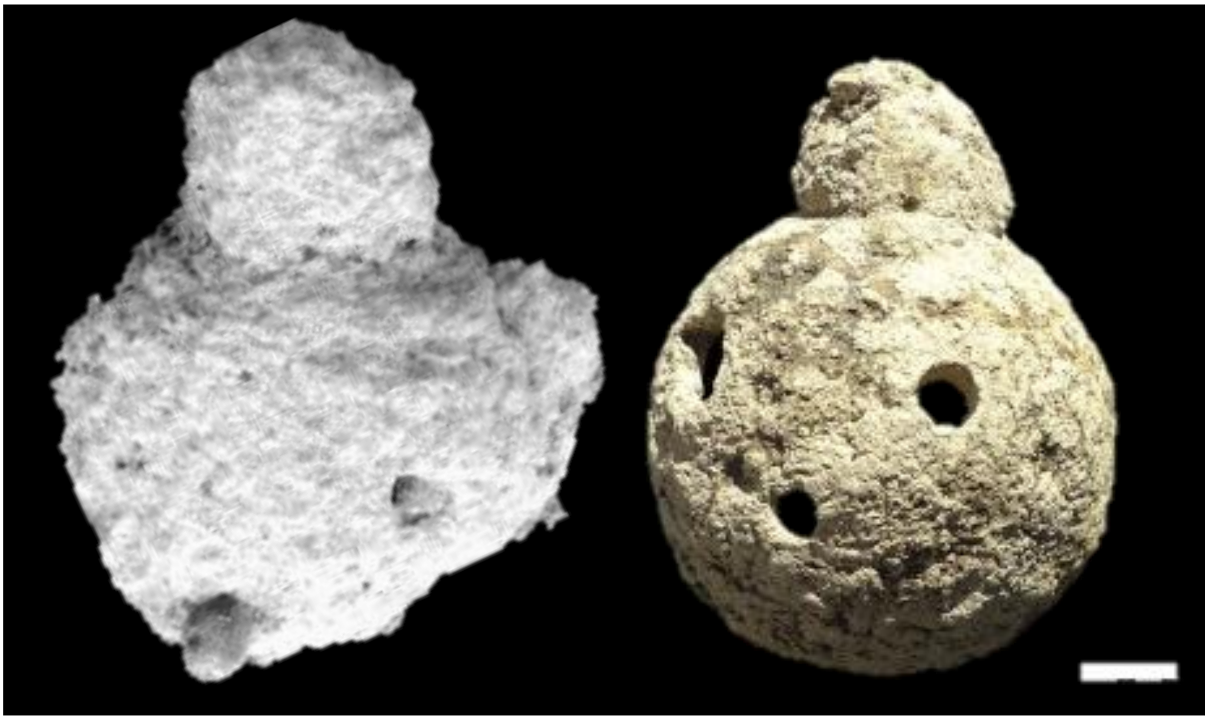

Figure 07: *Left:* Image Code 1M145850034EFF3505P2977M2M1 Combined spherical structures on Mars provide compelling morphological and structural evidence of potential trace activities, offering new insights into the planet's geological and possibly biological history? Captured by Rover Opportunity. *Right:* Types of Coprinisphaera akatanka preserved as a longitudinal half of the entire ball at Argentina.

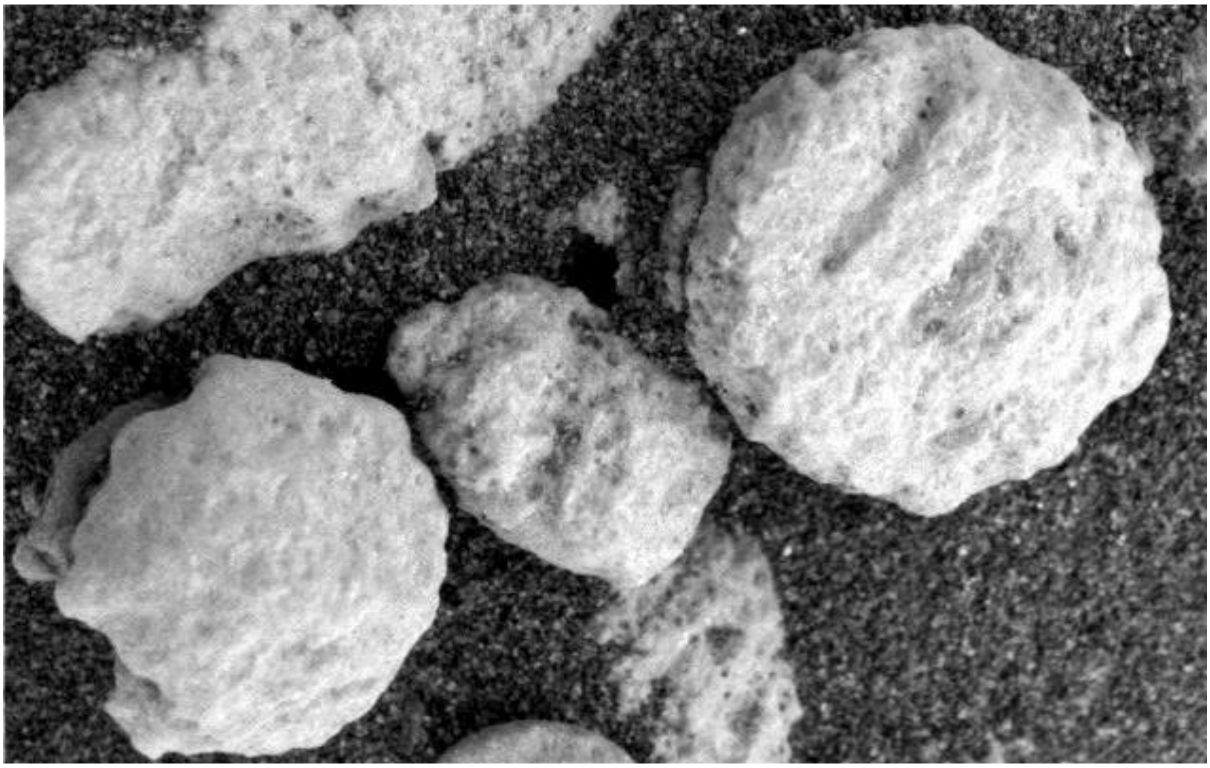

Figure 08.: Image Code: 1M145852648EFF3505P2957M2M1: Micro-boring or burrowing activities likely created these distinctive traces, potentially serving as survival or feeding mechanisms. This view highlights the intricate interplay between organisms and their substrate, offering insights into ecological behaviors and fossil preservation processes? Left corner bottom the observed view likely exhibits an altered tubular structure, suggesting potential modifications or natural transformations in its morphological configuration. Captured by Rover Opportunity.

Figure 09: Few different samples of *Kuphus polythalamius* (Shipway, J. R. et al .2017).

DISCUSSION

The niche trace environments depicted in Fig. 07 and Fig. 09 illustrate the distinct habitats of *Kuphus* sp. and *Coprinisphaera sp*., respectively. However, the presence of errored surfaces and unusual tip heads associated with Mars spherules suggests potential alterations caused by weathering, erosion, and prolonged exposure to high radiation. These factors may have contributed to the unique morphological features observed, highlighting the complex interplay between environmental conditions and trace fossil preservation.

In our ongoing development of a comparative model to understand the Martian environment, intriguing similarities have been identified between Martian geo-traces and certain fossils from Sri Lanka. Notably, the fossil and fossilized environment of *Kuphus arenarius*, commonly referred to as the 'Giant Teredo' (Family: Teredidae), discovered by Deraniyagala in 1969 at Arna Kallu, exhibit partial parallels with the environmental conditions associated with Martian spherules. Deraniyagala further speculated the presence of an Oligocene epoch in Sri Lanka, as *Kuphus* species are typically found in deposits dated to the lower Miocene or upper Oligocene periods. This connection was further reinforced in 2008 when a Giant Teredo fossil, exposed on a rock face following a blast, was discovered at the Aruwakkalu quarry site by Sampath Goonetilleke (PBD report, 2014). These findings provide a compelling basis for exploring potential analogies between ancient terrestrial ecosystems and the geological history of Mars.

The combined spherical structures observed on Mars, as depicted in Fig. 07 (Left: Image Code 1M145850034EFF3505P2977M2M1), exhibit compelling morphological and structural characteristics that suggest potential trace activities, offering profound insights into the planet's geological and possibly biological history. These structures bear a striking resemblance to the longitudinal halves of *Coprinisphaera akatanka,* as illustrated in Fig. 07 (Right), indicating possible parallels in formation processes. Furthermore, the black-tipped head and liner-errored surface features on these Martian spherical structures, shown in Fig. 08, closely resemble trace formations associated with *Kuphus polythalamius* (Fig. 09). The potential similarities in biotic and abiotic factors across extreme trace environments—ranging from Recent Mars to the Oligocene epoch in Sri Lanka and Early Pleistocene Morocco—suggest a possible convergence of ecological and geological processes. These findings provide robust petrological and trace evidence that supports the Eco Astronomy model, highlighting the potential for cross-planetary ecological and astrobiological correlations. This interdisciplinary approach underscores the significance of trace fossil analysis in understanding the evolutionary and environmental histories of both Earth and Mars.

Fig. 05 illustrates the presence of spherical concretions, commonly referred to as Moqui marbles, predominantly located in the arid regions of the American Southwest, specifically within Utah and Arizona. These geological formations are primarily composed of iron oxide and sandstone, resulting from diagenetic processes that involve the precipitation of iron-rich minerals within sedimentary layers. The formation mechanism of these concretions bears a striking resemblance to hematite spherules observed on Mars, as depicted in Fig. 04 and Fig. 06. This similarity suggests analogous geochemical processes involving the interaction of iron-rich fluids with porous sedimentary matrices under oxidizing conditions, potentially offering insights into the paleoenvironmental and diagenetic history of both terrestrial and Martian landscapes. The study of such concretions not only enhances our understanding of Earth's geological evolution but also provides a comparative framework for interpreting analogous features on extraterrestrial bodies

CONCLUTION

Recent studies have revealed striking similarities among three distinct sedimentary processes, offering profound insights into the fossilization mechanisms on Earth and their potential analogs on Mars. These processes include: (1) the fossilized environment of *Kuphus* species from the Oligocene epoch in Sri Lanka, (2) the fossilized environment of *Coprinisphaera akatanka* from the Early Pleistocene in Argentina, and (3) the formation of hematite spherules on Mars, as illustrated in Fig. 04, Fig. 08, and Fig. 06 (1M132266947EFF05AMP2987M2M1). The preservation of these features, particularly the hematite spherules on Mars, has drawn significant attention, with terrestrial analogs such as Moqui marbles providing critical context. However, it is essential to note that Moqui marbles, while informative, do not directly represent evidence for fossilization processes. This underscores the necessity of developing a robust comparative model that integrates paleontological and mineralogical data from both Earth and Mars to better understand the potential for fossil preservation in extraterrestrial environments.

Mars, considered a Pre-Harbor environment, presents a unique opportunity to explore the fossilization processes that may have occurred in the absence of a sustained biosphere. While traces observed on Mars have not yet been definitively verified as fossils, the application of Eco Astronomy models offers a promising framework for understanding preservation mechanisms in such environments. For instance, recrystallization-type fossilization, a process well-documented in terrestrial contexts, could potentially explain certain mineralogical features observed on Mars. This hypothesis highlights the importance of interdisciplinary approaches that combine paleontology, mineralogy, and astrobiology to unravel the complex history of Martian geology and its potential biosignatures.

Paleontologists, with their unique perspective on deep time and the processes governing the preservation of past life, are uniquely positioned to contribute to space exploration initiatives aimed at detecting extraterrestrial life. The techniques currently employed in the study of Martian rocks—such as spectroscopic and spectrometric analyses—have direct parallels in terrestrial paleobiology, fossil diagenesis, and geobiology. These methodologies have already led to significant advancements in astrobiology and Eco Astronomy, enabling the identification and characterization of minerals, organic matter traces, and potential biosignatures on Mars. However, to fully leverage these tools, it is imperative to conduct in-depth studies of lithologies, validate fossil biosignatures, and identify diverse forms of preservation and biominerals. Such efforts will not only enhance our understanding of Martian geology but also provide a foundation for detecting life beyond Earth. To address these challenges, a multi-faceted approach is required. This includes the development and sharing of case studies on the fossil record, with a focus on questions related to fossil diagenesis and paleobiology of astrobiological interest; the democratization of databases, particularly those containing spectroscopic and spectrometric data on fossils, biominerals, sediments, pigments, and rocks; the design and execution of geobiological and mineralogical experiments to confirm preservation patterns in rocks and fossils; and the creation of paleometric tests to establish more rigorous protocols for biosignature detection and fossil record analysis. These actions will not only bridge gaps in astrobiology but also foster a collaborative framework for advancing our understanding of life's potential beyond Earth.

The integration of paleontological and mineralogical data from Earth and Mars, coupled with the application of Eco Astronomy models, offers a transformative pathway for exploring the fossilization processes on both planets. By leveraging the expertise of paleontologists and the analytical tools of astrobiology, we can overcome the challenges of biosignature detection and contribute to the broader quest for life in the universe. This interdisciplinary approach not only enriches our scientific understanding but also underscores the critical role of paleontology in shaping the future of space exploration.

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