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Hypothesis Article

From Space Dust to Protocells: Micrometeorites in Early Cellular Evolution

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Abstract

Solid surfaces have long been considered catalysts in prebiotic chemistry, yet their physical energy has rarely been explored as a driver of protocell assembly. This opinion article highlights recent experimental advances demonstrating that oxide minerals, Hadean Earth analogs, and martian meteorite specimens autonomously promote the assembly and transformation of lipid protocells without chemical catalysis. Surface-adhered compartments form mechanically resilient protocell colonies, nanotube-connected protocell networks enabling direct molecular transport, and flat protocells with spontaneous fusion and compositional diversification—capabilities absent in cell-sized free-floating vesicles. Extending these findings to extraterrestrial materials, new results indicate that micrometeorites, with their freshly generated, rough, and porous surfaces produced during atmospheric entry, efficiently nucleate protocell assembly. Given the continuous global influx of micrometeorites and growing astrobiological evidence of organics in cosmic dust, I propose that micrometeorites represent previously underappreciated initiators of protocell development, linking early Earth environments with contemporary planetary science and the search for life elsewhere. Key Words: micrometeorite—protocell—lipid vesicle—lipid nanotube. Astrobiology 26, 219–226.

Surface-Derived Protocells

At the start of life, where the biological machinery of the advanced cells had most likely not yet developed, the innate energy of solid surfaces could have facilitated the self-assembly and shape transformations of protocells, most likely membrane-bound, life-like microcompartments evolving toward biological complexity.

Spherical compartments freely suspended in solution are the most common model system for protocells in experimental research today (Svetina, 2007; Gözen et al., 2022). Such primitive cell models are mostly satisfactory, considering that a spherical compartment provides a much simpler yet often sufficiently similar physical representation of more advanced cells in terms of size, shape, and fundamental behavior. Especially the lipid vesicles, which consist of simple amphiphilic biomolecules that likely existed on early Earth (Hargreaves et al., 1977; Rao et al., 1982, 1987; Jordan et al., 2019; Liu et al., 2020; Fiore et al., 2022), constitute a useful model for primitive cells at the origin of life.

Despite the recognized abundance of minerals and rocks on the Earth during the Hadean Eon (Morrison et al., 2018, 2023), the possible role of solid interfaces in protocell formation and development has largely been overlooked. Only a few reports have focused on membrane assembly on mineral nanoparticles (Hanczyc et al., 2007; Sahai et al., 2017).

Our recent experimental results reveal in detail how versatile and robust protocell morphologies readily form from lipid agglomerates on solid surfaces (Gözen, 2021; Gözen et al., 2022). Some example protocell structures include networks of lipidic compartments connected via nanotubes (Köksal et al., 2019b, 2020; Põldsalu et al., 2021), compact foam-like structures containing dozens of adjacent compartments that are reminiscent of microbial colonies (Chinmay Katke et al., 2023), meshes of membrane nanotubes (Bilal and Gözen, 2017; Köksal et al., 2019a), and dome-shaped subcompartmentalized vesicular structures (Spustova et al., 2021). Assembly and growth of protocells were enhanced specifically at the grain boundaries of analog Hadean Eon minerals, where the surface energy is the highest (Köksal et al., 2022).

In the context of abiogenesis, the role of surface energy in protocell assembly and shape transformations is often mistaken for mineral-mediated catalysis of lipids or other organic molecule synthesis. There is no catalysis occurring in the systems reviewed here; there are no chemical reactions and no rate increases in the assembly of protocellular compartments on surfaces when compared with vesicles that assembled in bulk.

Here, I refer only to the innate energy of solid interfaces that influence the self-assembly and shape transformations of protocells (Gözen, 2013). The surface energy is equivalent to the work required to generate the unit area of a particular surface, and is related to the surface tension, which is the force required to generate that unit area of a particular surface. The solid surfaces continuously tend to minimize their

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surface tension by making physical contact with other materials in the environment, which drives the adhesion and subsequent transformation of lipid membranes on these surfaces.

Note that membranous structures observed on solid surfaces, for example, nanotubes, can also spontaneously form in aqueous solutions without any surface contact. However, without complex scaffolding biocomponents such as protein fiber networks that most likely were not yet present on early Earth, such membrane structures would be instable and continuously tend to transform to spherical vesicles with minimal membrane surface-to-volume ratio, that is, minimal surface free energy. Solid surfaces provide optimal stability that allows the membranes to transform and maintain unusual yet beneficial membrane morphologies.

In biology, there is a tight coupling between structure and function such that the structure of a biological entity is optimized for its function (Konieczny et al., 2023). There is now experimental evidence that suggests that nontrivial protocell structures developed on terrestrial surfaces could have had benefits under certain selection pressures over free-standing, merely spherical compartments. Figure 1 schematically summarizes these key results and provides a comparison to the free-floating vesicles suspended in solution.

In case of sudden osmotic alterations in the surrounding liquid medium, while the spherical, single-shell compartments instantly collapse and disintegrate, surface-bound protocell colonies remain intact (Chinmay Katke et al., 2023; Fig. 1A). The protocells within a network are able to transport directly their internal content through lipid nanotubes (Gözen, 2019; Schanke et al., 2022; Fig. 1B) circumventing the need for exo-/endocytosis and any dependency on the surrounding medium for exchange of components, like bacteria do in quorum sensing (Chen et al., 2024). Moreover, the surface-bound protocells develop through a spreading process that involves flat giant unilamellar compartments with unique intervesicular fusion properties (Fig. 1C). From an energy point of view, unless inter-vesicular fusion is artificially induced, for example, by electrostatic attraction (Oshima and Sumitomo, 2017; Jõemetsa et al., 2019), Soluble N-ethylmaleimide-sensitive factor attachment protein receptors (SNARE) proteins (Diao et al., 2012) or complementary Deoxyribonucleic acid (DNA) (Rahman et al., 2022), it is not feasible for free-floating giant lipid vesicles in solution to spontaneously fuse upon physical contact. In contrast, flat compartments on surfaces spontaneously fuse and can easily overcome the high-energy barrier typical for pore

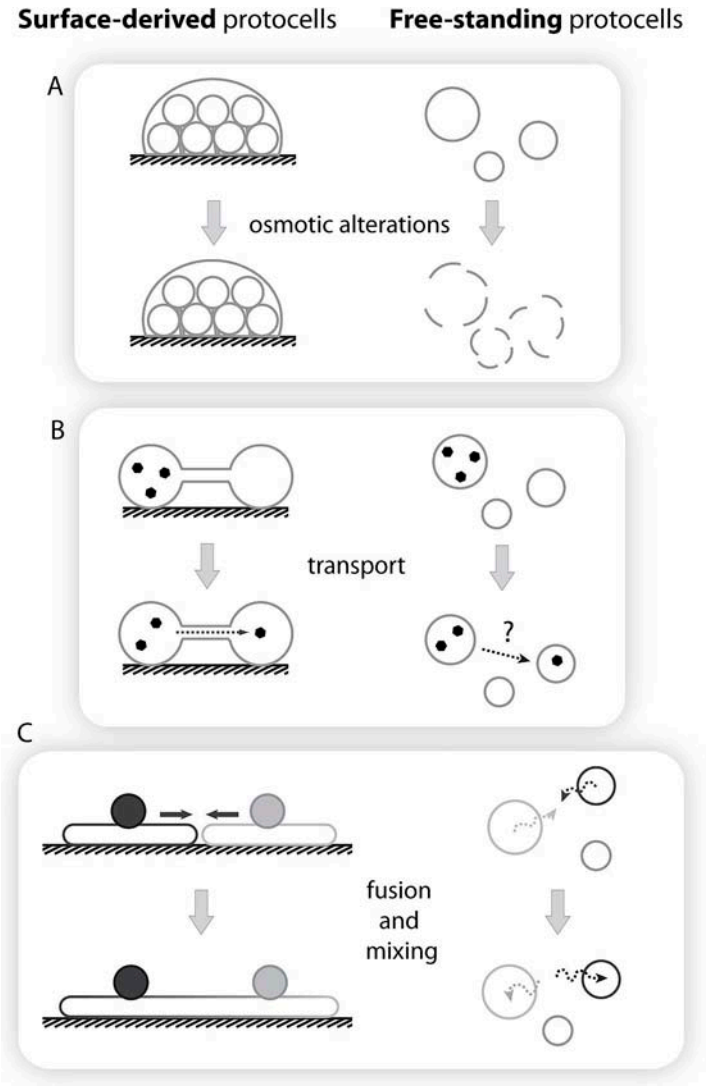

FIG. 1. Schematic summary of properties of surface-derived protocells with a comparison to free-standing vesicles in solution under similar conditions. **(A)** Protocell colonies enveloped in a lipid bilayer remain intact during sequential exposure to hypotonic and hypertonic solutions whereas the spherical compartments quickly disintegrate (Chinmay Katke et al., 2023). The drawing is oversimplified; in reality, vesicles break up into micelles or tubular fragments, rather than planar membrane fragments. **(B)** Protocells interconnected by lipid nanotubes can transfer components among each other via nanotubes (Schanke et al., 2022). For vesicles suspended in solution, there is no such direct channel; the cargo must be secreted to the solution and taken up by another vesicle. **(C)** Surface-adhered flat giant unilamellar compartments spontaneously fuse upon contact and their membrane lipids mix (Gözen et al., 2024). This structure later transforms into a population of dozens of progeny vesicles that consist of different ratios of the original membranes of the parent vesicles (not shown) (Gözen et al., 2024). Cell-sized unilamellar vesicles in solution, i.e., giant unilamellar vesicles (GUVs), do not spontaneously fuse and mix due to the high energy cost for fusion pore formation.

formation and fusion in lipid membranes. Large protocells of this type "prey" on smaller entities, consume them, develop further in size, and generate a wide compositional diversity of hundreds of progeny vesicles from two or more parent protocells of different composition (Gözen et al., 2024) (cf. Fig. 1C for the first step of a multiple-step process).

It is conceivable that surface-supported primitive cells could have been equipped with multifaceted abilities and structural features that would have been beneficial at the origin of life, and they might have emancipated themselves from the surface dependency once they had reached a complexity with features that could substitute the advantages the surfaces had once provided to them. Indeed, surface-supported protocell models have counterparts in complex cells. For example, tunneling nanotubes are ubiquitous throughout all domains of life (Rustom et al., 2004; Dubey et al., 2016; Gözen and Dommersnes, 2020) and are employed for exchange of small molecules, vesicles, proteins, organelles, viral genomes and pathogens between prokaryotic or eukaryotic cells (Panasiuk et al., 2018; Kolba et al., 2019; Peralta et al., 2013; Chakraborty et al., 2023; Angulo-Cánovas et al., 2024). Dense nanotubular networks in cellular biology are observed in the form of intracellular organelles in eukaryotes, such as endoplasmic reticulum, mitochondria, or chloroplasts. Some of these organelles have descended from once free-living single-cell organisms (Sagan, 1967; Diekmann and Pereira-Leal, 2013). It has also been hypothesized that the biogenesis of stromatolites in the rock record could have been derived from robust protocellular colonies, that is, "protocell aggregates" (Damer and Deamer, 2020).

Protocell Development on Extraterrestrial Interfaces

In the quest for interesting solid surfaces pertinent to the origin of life, I came across a martian meteorite specimen: Northwest Africa 7533. The uniqueness of this meteorite is that it was formed during the first 100 million years of Mars, at the same time the crusts of Earth and the moon formed (Humayun et al., 2013). Early wet Mars is considered highly relevant for the origin of water-based life, as it had liquid water, key elements relevant for life (C-H-N-O-P-S), transition metals and essential minerals such as Mg, Ca, Na, and K (Clark et al., 2021). Lipid compartment formation on this rare martian rock specimen gave the first experimental indication that materials from space are also capable of transforming amphiphile agglomerates into potential cell precursors (Köksal et al., 2022). The protocell compartments exhibited many of the transformation characteristics observed on Earth minerals, for example, spreading of lipid membranes, their transformation to lipid nanotube networks, formation of lipid vesicles, as well as soap foam-like densely packed compartments. Imaging and composition analyses confirmed that a lipid membrane adheres over the entire surface area of the meteorite specimen, rather than localizing at regions dominated by specific elements such as Fe, Al, Ca, and Mg. This result underscores the hypothesis that states that in addition to the elemental composition, many other parameters contribute to lipid-surface interactions, such as the surface topography and roughness (Roiter et al., 2008; Jõemetsa et al., 2019).

Beyond Mars, there are many environments within and outside of our solar system that are composed of Earth-like minerals, for example, the rocky planets, many of which are considered to be in a habitable zone where liquid water can be maintained on the surface. The icy moons Enceladus and Europa are being investigated for life signatures due to their subsurface oceans (Wickramasinghe et al., 2018; Hao et al., 2022). To reasonably address the question whether life—as we know it—is exclusive to our planet or exists/existed elsewhere, one approach has been to identify, through space and ground research, environments similar to Earth in terms of makeup and habitability. At least 287 million rocky planets within the Milky Way were recently estimated to have environmental conditions suitable for surface liquid water, allowing for the possibility of water-based life similar to ours (Bryson et al., 2021).

With regard to the hypothesis that solid surfaces could have been key to protocell formation on Earth, not only do we share mineral surfaces and surface water with numerous other planets inside and outside of our solar system, but also multiple tons of extraterrestrial objects reach our (and many other) planetary surfaces every year as meteorites. Several of these have been analyzed for their organic content, including the most extensively studied Murchison meteorite, as well as other carbonaceous chondrites (Botta and Bada, 2002; Pizzarello and Shock, 2010; Deamer and Pashley, 1989; Callahan et al., 2011; Furukawa et al., 2019; Lai et al., 2019; Oba et al., 2020, 2022; Waajen et al., 2024), and a ureilite from the Almahata Sitta meteorite fragment #4 (Callahan et al., 2011). Many organic materials were detected in these meteorites, including amphiphiles (Deamer and Pashley, 1989; Lai et al., 2019), nucleobases (Callahan et al., 2011; Oba et al., 2022), bioessential sugars (Furukawa et al., 2019), amino acids (Pizzarello and Shock, 2010; Botta and Bada, 2002), and many other compounds (Botta and Bada, 2002; Oba et al., 2020, 2022). Amino acids and phosphorus have also been detected in samples directly collected from the coma of comet 67 P/Churyumov-Gerasimenko and asteroid Ryugu (Potiszil et al., 2023; Altwegg et al., 2016).

Rather than just extracting amphiphilic molecules from the Murchison meteorite, Deamer placed these molecules in water and observed their self-assembly to spherical compartments (Deamer, 1985; Damer, 2019). In a recent experiment, anaerobic bacteria were grown in the presence of the Aguas Zarcas meteorite as the sole carbon, energy, and nutrient sources; direct transfer of carbon from the meteorite into microbial biomass was observed (Waajen et al., 2024). Although microorganisms are considered significantly more advanced than protocells, the results of the study show that the organic matter in meteorites was potentially available for incorporation into prebiotic cells.

In addition to large meteorites, the majority of which originate from the asteroid belt between Mars and Jupiter, there is a significant and continuous influx of micrometeorites. Micrometeorites are tiny particles (10–2000 μm) with different compositions and structures (Genge et al., 2008; van Ginneken et al., 2024). They represent a more diverse collection of cosmic materials, often containing components derived from comets and presolar grains (Seifert et al., 2022; van Ginneken et al., 2024). This compositional heterogeneity implies significant differences in their surface structures, mineralogy, and reactivity. For instance, micrometeorites originating from icy or volatile-rich parent bodies are likely to exhibit more amorphous or porous matrices, higher carbonaceous content,

and distinct catalytic mineral phases compared with their asteroidal counterparts (van Ginneken et al., 2017; Noguchi et al., 2022). Such textural and chemical features could influence their ability to take up and transform organic precursors under early planetary conditions.

Micrometeorites have been collected from various environments including the atmosphere, Antarctic, glacial and deep-sea sediments, and deserts (van Ginneken et al., 2024). A recently developed method by Larsen has enabled the recovery of micrometeorites from rooftops in urban environments (Larsen et al., 2018; Larsen, 2021). Approximately 10% of a total of 40 ± 20 kilotons of micrometeorites that reach our atmosphere every year has been estimated to survive the atmospheric entry and spread over our planet (van Ginneken et al., 2024). It has been suggested that micrometeorites accumulate and sediment in ponds that are favorable for prebiotic reactions (Maurette et al., 1995; Westall et al., 2018; Walton and Shorttle, 2021; Walton et al., 2024). Similar to the large meteorites, the micrometeorites also carry organic compounds that include the extraterrestrial amino acid α-aminoisobutyric acid (Brinton et al., 1998), polycyclic aromatic hydrocarbons (Clemett et al., 1998), and N-rich organic matter (Dartois et al., 2018; Haenecour, 2018).

My team has found that micrometeorites, specifically the porphyritic, scoriaceous, and barred olivine types, promote on their surface the autonomous formation of protocells from lipid reservoirs (Jesorka et al., 2025). Our research has shown that lipid compartments form in large numbers on the external surface and inside the cavities of micrometeorites like the one shown in Figure 2. The micrometeorite type shown there is largely composed of silicate minerals, rich in calcium, magnesium, and iron. We have found that the protocell-forming abilities of these particles are comparable to terrestrial particles of similar composition (Jesorka et al., 2025). As in earlier studies of lipid vesicle formation on mineral surfaces, vesicles that form on micrometeorites like the ones shown in Figure 2 are often interconnected and densely packed.

Our experiments have also revealed that the lipids derived from organisms representing different domains of life lead to the formation of different amounts of protocells. While archaeal lipids preferred to form protocells on micrometeorite surfaces over other types of surfaces, the bacterial lipids mostly avoided the micrometeorites (Jesorka et al., 2025). The distinction between archaea and bacterial lipids is important in the context of early evolution because while earlier hypotheses had considered archaea as more closely related to bacteria, it is now widely accepted that the eukaryotic cell originated from the Archaea (Spang et al., 2015).

Micrometeorites should not be considered as miniature versions of large meteorites as they are fundamentally distinct (van Ginneken et al., 2024). Upon atmospheric entry, cosmic dust particles encounter extreme heating due to hypervelocity motion ($\sim$11–72 km s^{-1}) and rapid compression of atmospheric gases around them, which can raise particle temperatures to $\sim$1700°C (Love and Brownlee, 1991; Rudraswami et al., 2015). As a result, the micrometeorites are heated throughout their entire volume, whereas meteorites experience heating that is largely confined to their outer surfaces. The complete heating of the micrometeorites results in surface textures and mineralogical features that are unique. Complete melting produces cosmic spherules with smooth, spherical surfaces, and minimal vesiculation (Taylor et al., 1998; Genge et al., 2008). Partial melting yields scoriaceous micrometeorites characterized by frothy, vesicular surfaces, and protruding relict grains, while unmelted micrometeorites retain angular, rough surfaces with characteristic magnetite rims formed during mild heating (Genge et al., 2008; Suttle et al., 2021). Surface structure is important for lipid membrane interactions because in addition to the elemental composition of the surface, the extent of surface contamination, roughness,

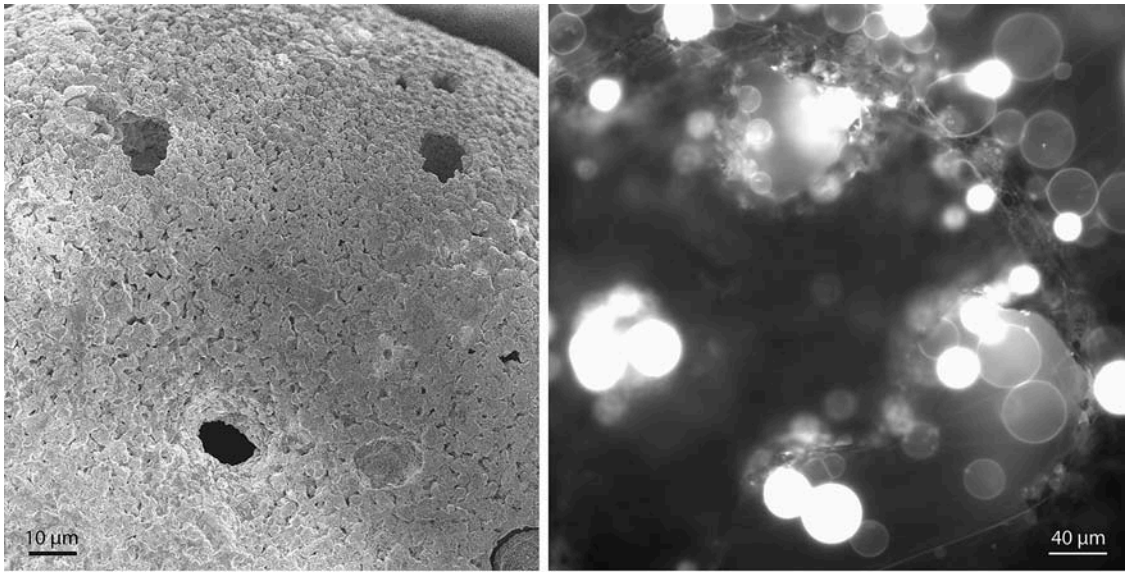

FIG. 2. Protocell formation on a scoriaceous micrometeorite. A scanning electron microscope image section of the micrometeorite (left), fluorescence microscope micrograph of protocells on the surface of the micrometeorite (right). Phospholipid membranes in the fluorescence micrograph are composed of Escherichia coli (*E.coli)* and soybean plant lipids, labeled with 1 wt% ATTO 655-DOPE. Unilamellar vesicles have only a thin fluorescent rim, while multilamellar membrane reservoirs are onion shell vesicles composed of densely packed lipid membranes.

and porosity are influential factors for membrane adhesion and spreading (Roiter et al., 2008; Jõemetsa et al., 2019; Villanueva et al., 2024). An example of the surface texture of a scoriaceous micrometeorite characterized by partly fused grains as well as microcavities is shown in Figure 2.

Hypothesis

I hypothesize that micrometeorites may have played a key and previously underappreciated role in protocell formation during the origin of life. While meteorites generally have a smooth surface, micrometeorites exhibit rough, vesicular surfaces with microscale porosity generated by whole-particle atmospheric processing. In contrast to terrestrial mineral surfaces, which on early Earth were already shaped by prolonged geological processing and environmental cycling, micrometeorite surfaces were freshly generated during atmospheric entry and continuously delivered across the planetary surface. Their small size and global dispersal would have provided abundant, mobile, and reactive interfaces for molecular adsorption. I propose that these unique surface properties favor lipid adhesion and organization, thereby promoting protocell assembly and facilitating prebiotic chemical interactions on the early Earth and potentially on other habitable planetary bodies. Laboratory studies like ours (Jesorka et al., 2025) can be designed to show how micrometeorites may have facilitated protocell formation not only on early Earth, but also in environments beyond the asteroid belt—such as on icy moons, comets, or planetary bodies where similar processes could occur. Comparative studies with basaltic lava and porous variants like pumice, which were ubiquitous rock types on early Earth, could also be designed to test this hypothesis.

It was previously hypothesized that on the early Earth, micrometeorites could have functioned as microscopic chemical reactors for the synthesis of prebiotic molecules (Maurette, 1998). The microcavities on the micrometeorite surfaces indeed could have acted as stable microenvironments as they are partially secluded from the external environment. The possible synergistic combination of such natural, self-supplied chemical microreactors with dynamic membrane compartments in direct contact with their surface can be considered as potential facilitators of a viable protocell development pathway at the origin of life.

Future Outlook

Looking at the formation of protocells that consist of surfactant shells is certainly only the beginning stages of this line of research. Surfaces have already been suggested as potential key contributors to the transition of prebiotic structures to living cells but only in the context of surface-based chemistry (Wächtershäuser, 1990, 2008; Pasek, 2017; Ritson et al., 2018; Gibard et al., 2019; Ritson et al., 2020; Trapp et al., 2026). The importance of surface energy for the assembly and transformation of lipid compartments has not yet been incorporated experimentally in this research. There are new compartment models where in an aqueous environment, through the openings in the basal membrane the internal volume of the protocell is directly exposed to the solid surface (Ryskulov et al., 2024). This might be a mechanism for producing encapsulating protocells in addition to the mechanism of vesicle formation and encapsulation of solutes during wet–dry cycles (Damer and Deamer, 2020). I propose that experiments that combine interfacial autotrophic chemical reaction systems (Wächtershäuser, 1990; Kitadai et al., 2018) with surface-derived, autonomously transforming protocells will be fundamental to drive the origin of life research to the next level.

Micrometeorites have the potential to occupy a special position in future origins of life and astrobiology research. With their characteristic surface texture, the organic material and catalysis-associated metals content, their mobility and accessibility, they have a potential that has not been adequately explored. They reach every location on the surface and have done continuously so since the formation of our planet. Being essentially mobile "prebiotic chemistry and self-assembly laboratories," they could have consistently accumulated in environmental niches and contributed there in some way to the development of protocells. If micrometeorites landed on relatively small bodies of water, such as small ponds, hot springs, clefts of rocks or other environments where water accumulated, it would have provided access to cycling systems with solutes. Furthermore, the cosmic dust not only reaches our planet but also other planets that include the exoplanets (Borin et al., 2017; Plane et al., 2018; Bonomo et al., 2019). This appears to be a tangible connection between our planet and extraterrestrial bodies we will probably not be able to reach in the foreseeable future. If a plausible connection between micrometeorites and the origin of life on Earth can be established, it would suggest that similar processes may have occurred—or may still be occurring—on other planets.

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