Prebiomics: An omics framework for prebiotic chemistry

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PREBIOTIC CHEMISTRY AND EXTRATERRESTRIAL ORGANICS

Since Friedrich Wöhler first synthesized urea in a laboratory setting in 1828, the formation and evolution of organic matter under abiotic conditions have been recognized as a central scientific field in the domain of origin-of-life studies. The historical timeline includes the Strecker synthesis in 1850, which demonstrated a reaction pathway from simple inorganic molecules to amino acids, and the Miller–Urey discharge experiment in 1953, which generated amino acids and amines in a simulated early Earth atmosphere. Subsequent studies, including those titled "prebiotic synthesis of amino acids/sugars/lipids/nucleobases/nucleotides/peptides" have explored how organic molecules formed and accumulated in interstellar or planetary environments. The term "prebiotic" was first coined in the 1970s to denote abiotic reaction and synthesis pathways of organic molecules. The field of prebiotic chemistry (Figure 1) has evolved into an interdisciplinary framework, integrating organic chemistry, geochemistry, astrochemistry, and biochemistry. The central question it seeks to address is how organic molecules essential for life were generated, enriched, organized, and chemically evolved before life emerged.

After more than fifty years of continuous astronomical observations, sample analysis, and laboratory simulations, it has become clear that complex organic compounds can form in abiotic interstellar and planetary environments.[1] For example, radio telescopes have detected carbon-chain molecules within the interstellar medium and in circumstellar shells. High-resolution mass spectrometry (HRMS) analysis of carbonaceous chondrites has revealed that individual samples can contain tens of thousands of soluble organic matter (SOM) molecules. Returned samples from the asteroid Ryugu exhibit SOM rich in amino acids and nitrogen-bearing compounds,[2] whereas Bennu samples indicate the presence of fourteen proteinogenic amino acids and five nucleobases.[3] Experimental studies have demonstrated that complex organic matter containing amino acids, sugars, and a variety of heteroatom-bearing compounds can be formed by irradiation of simple interstellar ice analogs composed of NH_3, H_2O, and CH_3OH (Figure 1).

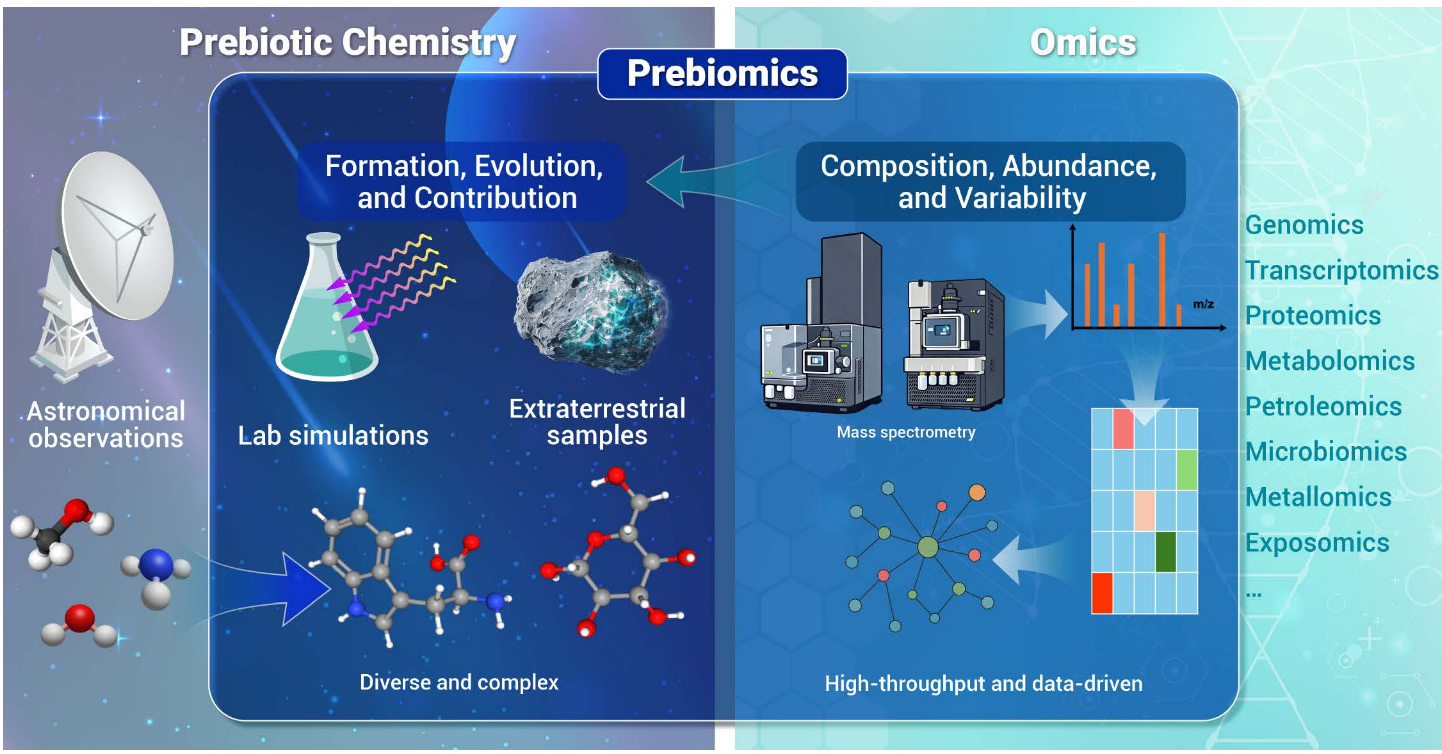

Figure 1. Conceptual framework of Prebiomics Omics provides methodological approaches, including high-throughput analysis and data-driven statistical methods, which have been widely applied in fields focusing on large-scale data and information. As prebiotic chemistry reveals increasingly complex extraterrestrial organic compounds, omics approaches have begun to be applied to prebiotic chemistry, here termed "prebiomics".

However, the complexity of extraterrestrial organic matter poses severe challenges to deciphering reaction pathways and synthetic mechanisms.[1,4] Individual samples may contain thousands to tens of thousands of distinct molecular formulas, while meteorites and asteroid samples differ markedly in origin and alteration history, making direct comparison and statistical generalization across samples difficult.[1] It is challenging to constrain the formation and evolution of such complex extraterrestrial organic matters. The following fundamental questions must be addressed: (i) How did precursors and interstellar environments influence the synthesis of prebiotic molecules and their subsequent transformation pathways? (ii) How did different planetesimals or parent-body processes shape the prebiotic chemical networks? (iii) How did these extraterrestrial organic reservoirs contribute to the origin of life on the early Earth?

PREBIOMICS: BRIDGING PREBIOTIC CHEMISTRY AND OMICS

At the same time, a similar challenge also arises in the life sciences when attempting to describe high-dimensional biological systems composed of large numbers of genes, proteins, and metabolites in a systematic and quantitative way. Since the 1990s, various omics approaches (Figure 1) have used high-throughput measurements and systems-level analysis to characterize the holistic, dynamic, and network properties of molecular components in biological systems. Genomics, transcriptomics, proteomics, and metabolomics have been firmly established as scientific disciplines. Because omics is inherently oriented towards large-scale data and information and enables the extraction of key patterns and insights from complex datasets, the field has undergone a substantial expansion over the last two decades, extending far beyond the domain of the life sciences, e.g., exposomics, microbiomics, metallomics, petroleomics, and many other -omics derivatives (Figure 1).

In this context, an increasing number of researchers are now applying omics-based concepts and techniques to the study of prebiotic chemistry. For example, proteomics-based strategies have been employed to investigate the formation of extraterrestrial peptides and their derivatives.[5] Metabolomics-based strategies, including ultra-high-performance liquid chromatography high-resolution mass spectrometry (UHPLC-HRMS) and desorption electrospray ionization high-resolution mass spectrometry (DESI-HRMS) imaging, have been used to characterize the composition, abundance, and distribution of SOM in meteorites and its evolution during aqueous alteration on the parent bodies.[4] Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR/MS) has been used to compare the composition and abundance of SOM in different meteorites or asteroids.[2,3] These studies have revealed the control of parent-body conditions on the evolution of extraterrestrial organic matter.[2,4] Together with mineralogical evidence for ancient brine environments, these observations indicate that carbonaceous asteroids once hosted widespread aqueous environments suitable for prebiotic chemical reactions.[3]

As these omics-based approaches continue to be developed and applied, a new disciplinary framework is emerging (Figure 1). Here, we term it "prebiomics", combining the terms "prebiotic" and "omics". It inherits the high-throughput and systems-level features of omics methods while explicitly targeting questions in prebiotic chemistry. The central goals of prebiomics are to systematically characterize the diversity of prebiotic organic molecules, to clarify the physical and chemical mechanisms that control their formation and transformation, to reconstruct their evolutionary histories in different systems, and, on this basis, to assess the plausible connections between these prebiotic organic reservoirs and the origin of life.

PROSPECTS FOR PREBIOMICS

At present, SOM in extraterrestrial samples that has been characterized is mainly restricted to small molecules with masses < 1000 Da,[2-4] and there is as yet no confirmed detection of biopolymers such as proteins or nucleic acids. Prebiomics can be technically analogous to metabolomics and can be divided into different branches such as untargeted prebiomics, targeted prebiomics, and spatial prebiomics. Untargeted prebiomics primarily employs UHPLC-HRMS,[4] FT-ICR/MS,[2,3] and nuclear magnetic resonance (NMR) to map the molecular composition and relative abundances of diverse SOM in samples. Targeted prebiomics, mainly based on UHPLC-HRMS and ultra-high-performance liquid chromatography triple quadrupole mass spectrometry (UHPLC-TQ/MS),[5] focuses on quantitative analysis of specific classes of prebiotic molecules, emphasizing quantitative accuracy, detection limits, and structural identification. Spatial prebiomics, based on mass spectrometry imaging (MSI) techniques,[2,4] focuses on organic–mineral interfacial processes and their co-evolution at micrometer scales. The integration of multiple analytical techniques with multivariate statistics and molecular networking, in conjunction with the coupling of molecular signatures to physico-chemical conditions and evolutionary history, will quantitatively constrain and elucidate the origin, evolution, and preservation mechanisms of extraterrestrial organic matters.

Methodologically, prebiomics still faces many challenges, including the intrinsic difficulty of structural identification, the transparency and reproducibility of data processing, and the open sharing of data and samples. In particular, extraterrestrial materials are typically available only in extremely limited quantities, imposing stringent requirements on analytical sensitivity and contamination control. Another central problem is how to constrain reaction pathways when definitive molecular structures remain unresolved. Nevertheless, the ultimate value of prebiomics will depend on the successful implementation of this concept as a reproducible and scalable research framework.

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AUTHOR CONTRIBUTIONS

Mingtan Dong initially proposed introducing an omics-based concept into the study of extraterrestrial organic matter. Wei Yang subsequently coined the term "Prebiomics" for this idea. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

Wei Yang is an Editorial Board member of The Innovation Geoscience and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.