Applications of Synchrotron Techniques in Astrobiology: Analyzing Ancient Fossils to Unravel Biosignatures and Extraterrestrial Life

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Astrobiology has emerged as a multidisciplinary field, focused on understanding the origin, evolution, and distribution of life in the universe. In recent years, synchrotron-based techniques have revolutionized the study of ancient fossils on Earth and offer promising implications for astrobiological research. This work presents a comprehensive review of the applications of synchrotron techniques in astrobiology, specifically in the analysis of ancient fossils as proxies for the study of biosignatures and the search for extraterrestrial life on Mars and other planetary bodies.

Synchrotron techniques, including X-ray diffraction (XRD), X-ray fluorescence (XRF), X-ray absorption spectroscopy (XAS), and X-ray computed microtomography (microCT) have been extensively employed to study microfossils, stromatolites, and other ancient biomarkers. These non-destructive, high-resolution approaches facilitate the identification of biogenic minerals, organic matter, and micro-structures elucidating the geological, geochemical, and paleoenvironmental context of ancient life. The Perseverance and Curiosity rovers, and the ExoMars mission have established the presence of sedimentary rocks and aqueous environments on Mars, hinting at the possibility of past habitability. Synchrotron-based techniques could be instrumental in characterizing Martian biosignatures, including potential microfossils, biominerals, and biomolecules, by examining samples returned to Earth or through in situ measurements on future missions. Furthermore, synchrotron techniques can be utilized to simulate Martian surface conditions, such as ultraviolet radiation and extreme temperatures, to assess the survivability and detectability of biosignatures. In addition to Mars, astrobiological research has identified other planetary bodies with potential habitable environments, such as Europa, Enceladus, and Titan. Synchrotron techniques can be employed to study the composition and structure of organic matter in the icy shells of these moons, as well as the potential for biogenic materials in the plumes ejected from their subsurface oceans.

In conclusion, synchrotron-based techniques have transformative potential for astrobiology, particularly in the study of ancient fossils as proxies for biosignatures and the search for extraterrestrial life. Further development of these techniques, alongside advancements in space exploration, will undoubtedly advance our understanding of the potential for life beyond Earth and deepen our comprehension of the diverse environments that can support it.