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Habitability of Mars: Planetary Conditions for Life

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Abstract

The abiotic and biological pathways for methanogenesis on Mars are surprisingly similar. Both mechanisms use CO_2 and H_2 as starting materials and result in the production of CH_4. However, the geochemical pathway has a high kinetic barrier and the reaction is slow. A biological pathway "quickens" this process. The total flux of 1.7×10^7 mol year^{-1} that is needed to maintain the observed CH_4 in steady state in the atmosphere is examined in the context of fluxes of He from the interior of the planet and photochemical production of H_2 in the atmosphere. Future experiments that can distinguish the abiotic versus biological origins of CH_4 on Mars are discussed. Methanogenesis on Mars may serve as the "hydrogen atom" for the origin of life. Such discussions are not restricted to Mars and can be extended to other worlds with incipient planetary conditions for life and we discuss implications for the habitability of Enceladus.

1. Introduction

That "Life is flux" is clear from our present understanding of the terrestrial biosphere (e.g., Schlesinger 1997). Here we pursue this concept in our search for extraterrestrial life, focusing on Mars where the order of magnitude of the flux of organic carbon has been deduced from recent observations. The possibility that the ~10 ppbv of methane (CH_4) on Mars is biogenic has created great excitement as to whether it is biogenic or not (Krasnopolsky 2004; Formisano et al. 2004; Mumma et al. 2009). Since the lifetime of CH_4 on Mars is about 300 years (Summers et al. 2002; Wong and Atreya 2003) this indicates a source of 2.2×10^5 molecules cm^{-2}s^{-1}, or 1.7×10^7 mol year^{-1}. For comparison, the CH_4 flux generated by the terrestrial biosphere is 10^{14} mol year^{-1}. As there is no evidence of life on the surface of Mars, any hypothetical microbes there must reside beneath the surface. The carbon flux cited above might serve as a link between a putative subterranean biosphere on Mars and what we can measure above the surface. The alternative of course is that the methane anomalies relate either to an inorganic origin or are being released from some occluded source.

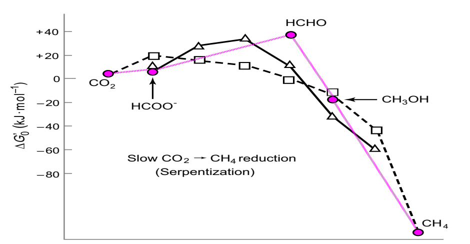

Figure 1a. Free-energy profile of the geochemical pathway (in purple) to methane (Seewald et al., 2006) is contrasted with the reduction profiles of the acetogenic (triangles) and methanogenic (squares) that both use the acetyl coenzyme-A pathway (Maden, 2000). We can think of the geochemical pathway as a chemical siphon while the much more rapid biochemical pathways are driven by chemiosmosis over the intermediate formate and formaldehyde. Adapted from Maden (2000).

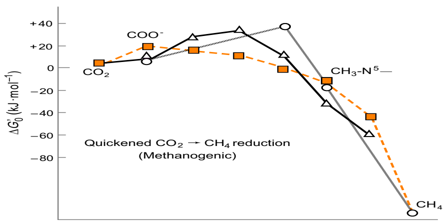

Figure 1b. Free-energy profile of the methanogenic reduction pathway (in orange) taken by the methanoarchaea compared to the sluggish geochemical pathway (open circles) and the acetogenic pathway (triangles). H_4Folate is tetrahydrofolate and H_4MPT is tetrahydromethanopterin. Adapted from Maden (2000).

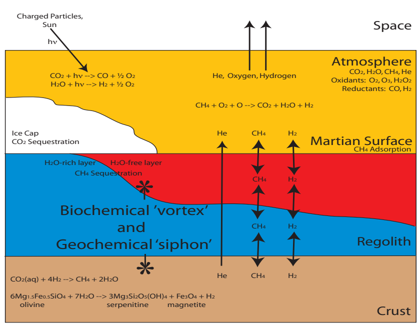

Figure 2. Schematic diagram for methanogenesis on Mars

2. Summary and Conclusions

We examine the planetary environment of Mars and the abiotic and biological mechanisms for producing CH_4. The main ideas are summarized in Fig. 2. He and H fluxes show that Mars is an active planet geochemically and photochemically. The serpentinization reaction produces hydrogen, which together with atmospheric or geochemical CO_2, provides the feedstock for methanogenesis.

There are many ways to distinguish between the abotic and biological origins of CH_4 on Mars. Allen et al. (2006) discuss the use of isotoplogues and family of alkane abundances to distinguish between competing sources. We point out the two key discrimants: efficiency and byproducts. The former could be tested by the measurements of H_2 and CH_4 fluxes. The products of microbial metabolism associated with CH_4 synthesis include acetate, acetic acid and H_2S, which should be absent in the abiotic process.

Perhaps the most exciting implication of CH_4 on Mars is that it is the “hydrogen atom” for the study of origin of life, while on Earth the pristine conditions have long ago been modified by the emergence and evolution of life. The Martian chemical environment is simple, and methanogenesis is among the simplest biological processes. How far Mars has gone from abiotic to biological synthesis of CH_4 has profound implications on the existence of extraterrestrial life in our solar system and extrasolar systems. This would provide overriding goals for future space exploration.