The Rise and Development of Habitability Through Formation of Bioorganic Compounds on the Early Earth via Solar Energetic Particles

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Geochemicl evidence suggests that life on Earth was generated about 4 billion years ago. There has been a number of controversies surrounding the origin of life. First, this is the process which is referred to as *a faint young Sun paradox*: why the early Earth was not frozen under the 30% fainter young Sun at 4 Ga [1]? Secondly, how bioorganic compounds such as amino acids were prebiotically formed in the atmosphere and surface of the primitive Earth, which is now thought to have been only slightly reducing (e.g., N_2 + CO_2+ H_2O + trace of reducing gases) [2].
Maehara et al. 2012 reported that frequent superflares were observed in many young and magnetically active solar-type stars [3], which implies that the young Sun also had undergone through the phase of energetic and frequent flares, which would have been associated with coronal mass ejections and high-fluence hard-spectra solar energetic particles (SEPs) [4]. Such high-energy particles would have ionized the planetary atmospheres and drive chemical reactions in planetary atmospheres. Airapetian et al. (2016) developed a model suggesting that a chain of reactions driven by SEPs in nitrogen and carbon dioxide rich atmosphere could have formed N_2O, a strong greenhouse gas in the early Earth atmosphere [5].
We previously reported that Galactic Cosmic Rays (GCRs)could be an effective energy source for prebiotic synthesis: Amino acids and some nucleic acid bases were formed when a slightly reducing gas mixtures simulating early Earth atmosphere were irradiated with high-energy particles [5, 6]. We estimate that flux of SEPs was 4-5 orders of magntitude greater at 1-5 Gev than that of GCRs at 4 Ga [8]. Here, we report on the experiments on proton irradiation of simulated primitive mildly reducing Earth atmosphere to study the impact of SEPs, and analysis of products including N_2O and amino acids. The initial gas mixtures used here were mixtures of N_2, CO_2, CO (or CH_4), and H_2O with various mixing ratios. Protons were generated from a Tandem accelerator or a van de Graaff accelerator (Tokyo Institute of Technology). Gaseous products were analyzed by GC/MS, and amino acids were determined by ion-exchange HPLC after acid hydrolysis. Carboxylic acids were determined by GC/MS after derivatization.
When 400 mL mixture of N_2 (700 Torr) and H_2O vapor (ca. 20 Torr) was proton-irradiated (total energy deposit: 3.2 kJ), 0.82 Torr of N_2O was formed. N_2O has much larger global warming potential than CO_2 and CH_4, N_2O could make the Earth warm under the faint young Sun. When mixtures of N_2, CO_2 and H_2O were irradiated, amino acids were not detected but carboxylic acids were detected. When CO or CH_4 were added to the gas mixtures, amino acids were formed, even molar ratio of CO (or CH_4) was much less than that of CO_2. Uracil was also found in the products after proton irradiation of mixtures of CO_2, CO, N_2 and H_2O, whose yield was proportional to CO molar ratio. Thus, we can say that SEPs and GCRs were very effective energies for prebiotic formation of bioorganic compounds in slightly reducing atmospheres. Since the energy flux of SEPs from the young Sun was expected to be much greater than that of GCRs, SEPs would have been most promising energy sources for prebiotic production of N-containing bioorganic compounds such as amino acids and nucleic acid bases.
Also, when high-energy (> 300 MeV) protons in GCRs or SEPs penetrate the planetary atmosphere and collide with atmospheric molecules, spin-polarized muons are formed, which could produce enantiomeric

excesses of amino acids in terrestrial biosphere [9]. Thus, SEPs might be considered as efficient sources of homochirality of biomolecules. We are currently investigating whether spin-polarized muons can produce enantiomeric excesses of amino acids by muons irradiation at Materials and Life Science Facility (MLF) of J-PARC, Japan.

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