Evolution of organic matter in carbonaceous asteroids driven by formose-type reaction

*Yoshihiro Furukawa[1]

1. Tohoku University

Carbonaceous asteroids are among the most primitive bodies in the solar system and have attracted significant attention as the parent bodies of carbonaceous chondrites, which are meteorites believed to have delivered water and organic compounds to Earth. In recent years, advances in analytical techniques, novel theoretical frameworks, and the analyses of samples returned by Hayabusa2 and OSIRIS-REx have greatly improved our understanding of how organic matter evolves within carbonaceous asteroids. This presentation introduces these developments, in particular investigations related to the reactions that formed soluble organic compounds, and discusses future prospects for elucidating the nature of organic matter in carbonaceous asteroids.
Among the organic compounds found in meteorites, sugars such as ribose had previously been identified in the Murchison meteorite. However, recent analyses of Bennu samples have confirmed, as expected, that asteroids that have undergone extensive aqueous alteration contain lower overall sugar abundances, with glucose more abundant than ribose. It had long been hypothesized that sugars were produced through the formose reaction, a sequential polymerization of low-molecular-weight aldehydes such as formaldehyde and glycolaldehyde, and the Bennu results further support this hypothesis, providing decisive evidence that the formose reaction occurred within the asteroid's interior.
This reaction is catalyzed by Ca^{2+} and Mg^{2+} ions and proceeds as a stepwise reaction in alkaline aqueous solution, conditions that are consistent with the aqueous alteration environment of carbonaceous asteroids. The reaction products include carbonaceous solid materials insoluble in acids and organic solvents, similar to the insoluble organic matter (IOM) found in meteorites. It has also been demonstrated that when ammonia participates in this reaction, multiple amino acid species are produced. Furthermore, the difference in carbon-isotopic composition between these product amino acids and IOM-like materials has been reported to be comparable to that observed in actual meteorites. In addition, carboxylic acids and amines, both of which are found in meteorites, have also been shown to form through this reaction.
Amino acids in meteorites have traditionally been inferred to form via the Strecker reaction, which involves aldehydes, ammonia, and hydrogen cyanide (HCN). HCN is a key precursor for nucleobases and has been detected in molecular clouds and comets, making its involvement in organic evolution reactions within asteroid interiors chemically plausible.
Moreover, the formose reaction is known to produce a wide variety of homologs through its sequential reaction mechanism. The presence of such homologs has also been revealed by recent high-resolution mass spectrometric analyses of meteorite extracts. Taken together, the formose reaction, as the primary sugar-forming pathway, may have served as the central axis of organic matter synthesis in asteroid interiors, reacting with other low-molecular-weight organic compounds to generate a diverse array of both soluble and insoluble organic molecules. Recent studies have also suggested that these reactions may have been promoted by gamma-ray irradiation from the decay of short-lived radionuclides following asteroid accretion.
On the other hand, formose-type reactions may also have proceeded in pre-accretionary ices driven by ultraviolet irradiation. Considering this possibility, the reactions before and after accretion may not be entirely distinct; rather, they may represent different stages of the same sequential formose reaction pathway, distinguished primarily by how much of the starting materials were consumed and how far the reaction progressed. We anticipate that continued advances in constraining the molecular-level and

intramolecular isotopic compositions of meteoritic organic matter, combined with improved estimates of the distribution and isotopic signatures of low-molecular-weight organic compounds in the protosolar disk, will eventually enable us to decipher the origins of organic matter in asteroids and comets.