

Editorial

The Origin of Sugars

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Life as we know it on Earth is anchored by four fundamental classes of biological macromolecules. These pivotal, carbon-based molecular pillars include proteins (based on amino acid), DNA and RNA (whose “letters” are represented by nucleobases), lipids and carbohydrates. The last named form the backbone of DNA and RNA and play a fundamental role in metabolic processes.

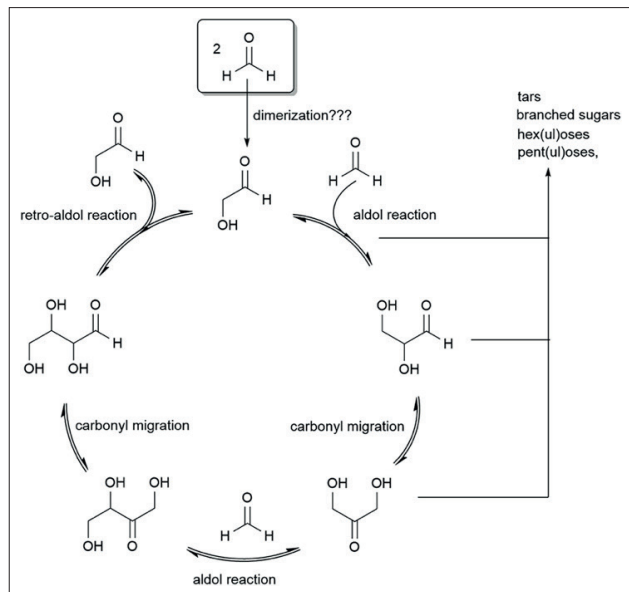


Figure 1. The initial formation of glycolaldehyde from glyoxylate is followed by a series of repetitive (1) aldol condensations with glyoxylate, (2) carbonyl migrations, and (3) decarboxylations, without the disadvantages of formaldehyde-based reactions.

One of the main questions about the origins of life is how these molecules formed. In laboratory experiments, simulating prebiotic conditions yield only low

concentrations of carbohydrates, certainly insufficient to support the pivotal role that they actually play. Many scientists believe that the first sugars originated from reactions involving formaldehyde—specifically the “formose” reaction (crisis of “formaldehyde” and “hexose”). However, this molecule triggers uncontrolled side reactions, and its high reactivity, under the conditions hypothesized for the early Earth, presents further challenges. A second theory was formulated in 2007: a scenario based on the “glyoxylate reaction,” in which glyoxylate first reacts with itself to form glycolaldehyde. Researchers suggest that glyoxylate, glycolaldehyde, their byproducts, and other simple compounds could have continued to react with one another, finally producing simple sugars and other products [1].

Alongside the hypothesis that carbohydrates formed on Earth, there is another hypothesis suggesting an exogenous origin. This hypothesis is supported by the detection of sugars essential for life, such as ribose and glucose, in meteorites and, more recently, on the asteroid Bennu [2] and on Arrokoth, a Kuiper belt icy body originated during the formation of the Solar System 4.6 billion years ago [3]. Did these sugars form on these minor bodies, or, more likely, they were present in the cloud from which the solar system originated? To Answer this question requires detecting sugars and/or their precursors in the interstellar medium (ISM). The ISM is a remarkable chemical factory, where over 340 molecules have been detected, including large aromatic species. Several of these molecules—such as urea, hydroxylamine, and ethanolamine—are directly linked to the chemistry of the origin of life, as they are considered precursors to ribonucleosides and lipids. However, no sugars had been observed to date. A major obstacle in searching for interstellar sugars has been the lack of data

regarding energy transitions between quantized rotational states in the gas phase. Such data are essential for astronomical identification via radio telescopes, but they are extremely difficult to obtain, as sugars are thermally fragile and highly hygroscopic—properties that hinder their handling and conventional thermal vaporization.

This limitation has recently been overcome thanks to ultrafast laser vaporization, which enabled the gas-phase rotational characterization of ribose and 2-deoxyribose, as well as erythrulose. It is precisely the last one that was recently detected through ultrasensitive, broadband spectral surveys of the molecular cloud G+0.693–0.027 in the Galactic Center of the Milky Way (Figure 2)—located approximately 26,000 light-years away—using the Yebes 40 m and IRAM 30 m radio telescopes (Figure 3) [3].

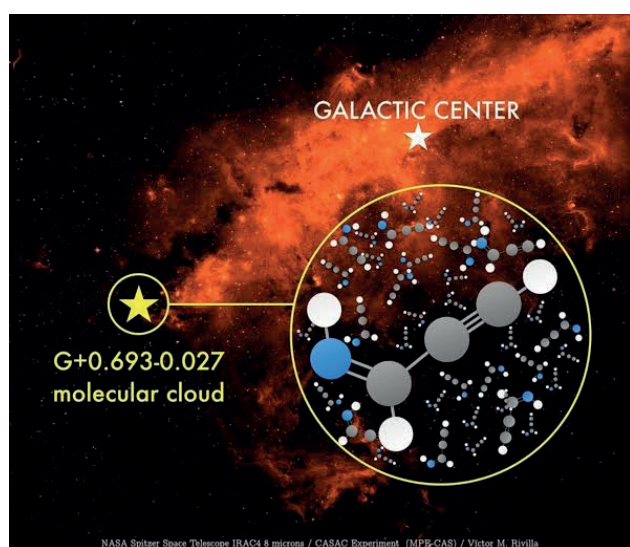


Figure 2. The G+0.693–0.027 molecular cloud is located within the Sgr B2 star-forming complex; it spans 150 light-years and has a mass 3 million times that of the Sun, situated at the center of our Galaxy. Copyright NASA.

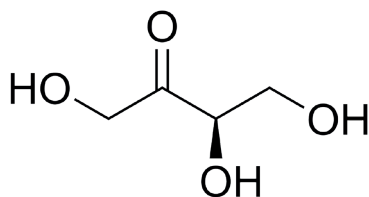


Figure 3. Structural formula of erythrulose, IUPAC name (R)-1,3,4-trihydroxybutan-2-one

Erythrulose, with 14 atoms in its structure, represents the largest non-cyclic molecular species identified to date in the ISM and is the first detected molecule

containing four oxygen atoms. It is also the first sugar and the second chiral molecule reported in the ISM, following propylene oxide. Its presence in the interstellar medium not only provides direct evidence that complex, chiral species can form under interstellar conditions, but also advances our understanding of the scale of interstellar chemical complexity, suggesting that other prebiotic (and potentially chiral) molecules could form and survive even in these extreme conditions. This sugar can serve as a basis for the formation of ribonucleotides—the building blocks of RNA. Ketoses like erythrulose can readily isomerize into their corresponding aldoses (namely, threose and erythrose) in aqueous environments, a transformation crucial for the formation of ribose. What is the pathway in the ISM for synthesizing this carbohydrate? Recent laboratory experiments of irradiated methanol ices find out that sugars with up to six carbon atoms can be obtained from smaller sugar and sugar-derivative fragments (e.g. C3 sugar precursors) [3]. In this molecular cloud the C3 sugars glyceraldehyde and dihydroxyacetone are at least 8–17 times less abundant than erythrulose, suggesting that they are not dominant precursors. More abundant building blocks of this C4 sugar are present as glycolaldehyde and ethylene glycol in G+0.693. Therefore, these substances can be the precursors of Erythrulose on the surface of interstellar dust grains. Consequently, once formed, erythrulose and other sugars could be incorporated into the planetesimals that give rise to bodies in the outer Solar System, such as Kuiper Belt objects.

The discovery of chiral erythrulose supports also the idea that small enantiomeric excesses measured in meteorites (on the order of a few percent) may originate in extraterrestrial environments, which could have contributed to the emergence of biological homochirality on the early Earth, through subsequent chemical amplification processes. Thus, erythrulose might have arrived on Earth during the Late Heavy Bombardment between 4.1 and 3.9 billion years ago. Although the extent and intensity of the Late Heavy Bombardment have recently become questionable, simulations of Earth's impact history show that biopoiesis—the process describing the development of living matter from non-living organic matter—could have occurred over a much broader time-frame, between 4.45 and 3.9 billion years ago. Since glycolaldehyde, small sugars, and sugar derivatives have been shown to survive meteorite impacts, the presence of erythrulose in interstellar space reinforces the hypothesis of an exogenous origin for the sugars relevant to the synthesis of early nucleic acids. The presence of erythrulose on the surface of the early Earth and its rapid isomerization into threose (Figure 4) support its involvement in the formation of threose nucleic acid

(TNA), a structurally simpler RNA analogue [5]. Threose nucleic acid has been synthesized in the laboratory and, in the context of the origin of life, has been proposed as one of the polymers that may have played a role in a pre-RNA world.

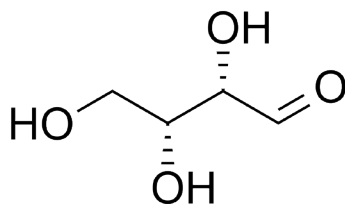


Figure 4. Structural Formula of Threose

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- 3) Zhang C. et al. (2024) Ionizing radiation exposure on Arrokoth shapes a sugar world *PNAS*, 121, e2320215121 <https://doi.org/10.1073/pnas.2320215121>
- 4) Jiménez-Serra I et al (2026) Detection of a four-carbon sugar in interstellar space *Nat. Astron.* <https://doi.org/10.1038/s41550-026-02905-7>.
- 5) Threose nucleic acid (TNA)—or (L)- α -threofuranosyl nucleic acid—is a nucleic acid similar to DNA and RNA but differs from them in the composition of its backbone, which consists of repeating threose units linked by phosphodiester bonds, rather than ribose or deoxyribose.

