Comparative Investigation of the Mechanisms of Formose-like Reaction for Complex Organic Molecules

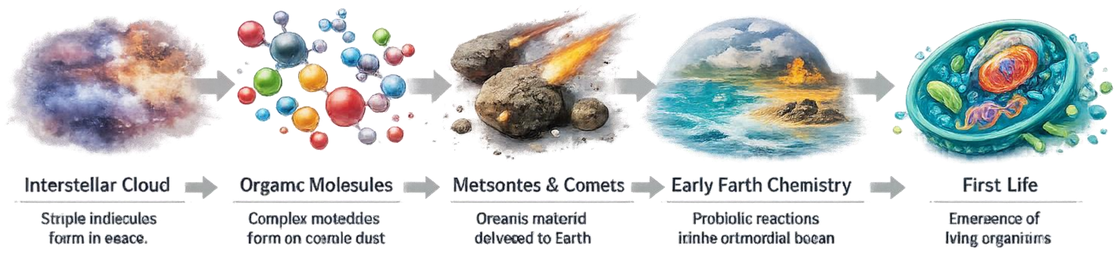
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Abstract

The formation of complex organic molecules (COMs) in interstellar environments is essential for understanding the chemical evolution leading to the origin of life. Ribose, a fundamental component of ribonucleic acid (RNA), is proposed to form through formose-like reactions from simple precursors such as formaldehyde (H_2CO). In interstellar molecular clouds, these molecules can accumulate as ice mantles on dust grains and undergo photochemical processing driven by vacuum ultraviolet VUV radiation generated through cosmic-ray interactions with molecular hydrogen. In this study, formose-like reactions were comparatively investigated under two activation conditions: thermal heating at 60 °C and VUV irradiation in a vacuum chamber. Paraformaldehyde and calcium hydroxide were used as the primary reactants. a characteristic yellow coloration typically associated with formose-type reactions, indicating progression of the formose reaction. In contrast, the VUV-irradiated samples showed no visible color change; however, Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy revealed spectral features distinct from the control group. These results suggest that VUV irradiation may induce alternative reaction pathways for sugar-related products under simulated interstellar conditions. This work provides insight into the potential role of photo-driven chemistry in prebiotic molecular evolution and supports future experiments designed to simulate sugar formation on interstellar dust grains.

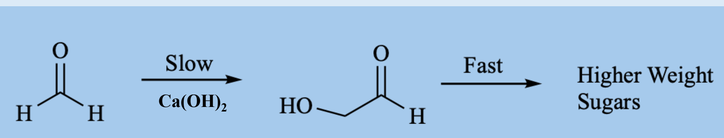
Introduction

❑ From interstellar cloud to life



The origin of life on Earth is one of the most fundamental questions in science. Studies in astrochemistry suggest that many organic molecules essential for life may have originated in interstellar molecular clouds. These clouds contain simple molecules such as H_2, CO, NH_3, H_2O, CH_3OH, and H_2CO which can undergo chemical reactions on the surfaces of cosmic dust grains under the influence of ultraviolet radiation and cosmic rays. Over time, these reactions lead to the formation of more complex organic molecules, including prebiotic compounds. Some of these molecules are incorporated into comets and meteorites and later delivered to early Earth. Once on Earth, they may have participated in further chemical evolution, eventually leading to the emergence of life. Understanding the chemical processes that occur from interstellar clouds to planetary environments is therefore crucial for explaining how the building blocks of life were formed and distributed throughout the universe.

❑ Formose Reaction



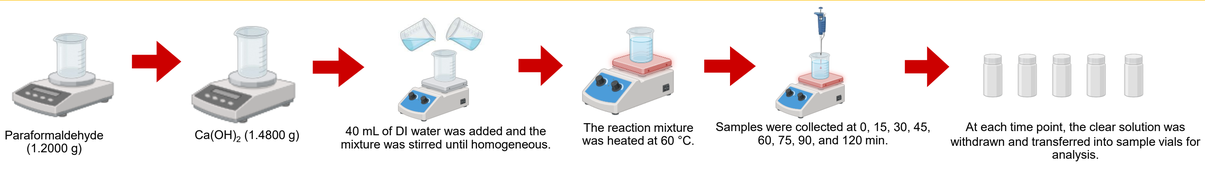
The formose reaction is a complex network of base-catalyzed reactions in which formaldehyde undergoes self-condensation to produce a variety of sugars and sugar-like compounds.The first, a slow step, is the reaction of formaldehyde to form glycolaldehyde. The second reaction, which is fast and autocatalytic, involves the formation of many higher weight aldoses and ketoses from lower weight species. The primary interest in the formose reaction lies in its ability to produce sugars, which may be related to the origin of life and the RNA world hypothesis.

Research Objectives

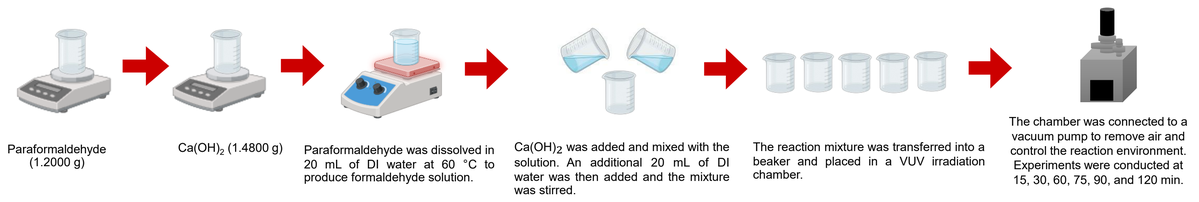
- ❑ To investigate the effects of Vacuum Ultraviolet (VUV) radiation on the formose-like reaction of formaldehyde (H_2CO) solution under vacuum conditions.
- ❑ To compare the efficiency of VUV radiation and thermal energy in driving the synthesis of complex organic molecules (COMs).
- ❑ To analyze the chemical structural changes of the resulting products using Fourier Transform Infrared (FTIR) spectroscopy.
- ❑ To study the role of VUV radiation in inducing radical formation and its impact on the reaction pathways.

Methodology

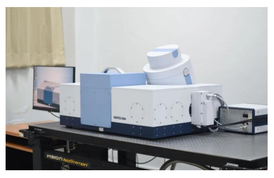
Thermal conditions



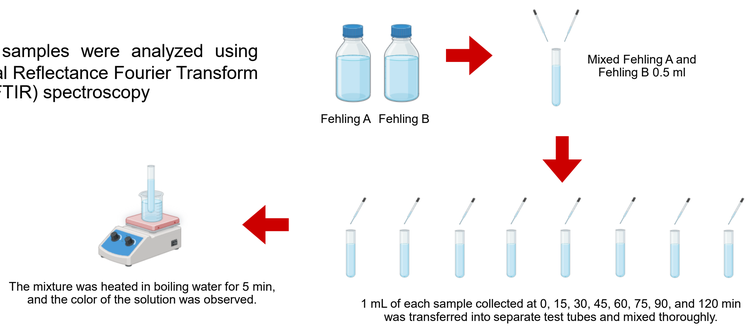
VUV irradiation



Characterization and Test

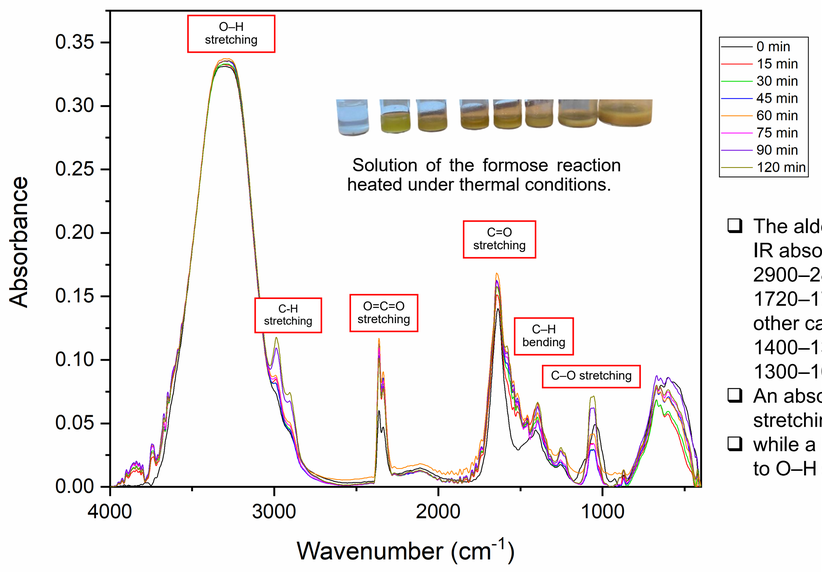


The collected samples were analyzed using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy



Results and Discussion

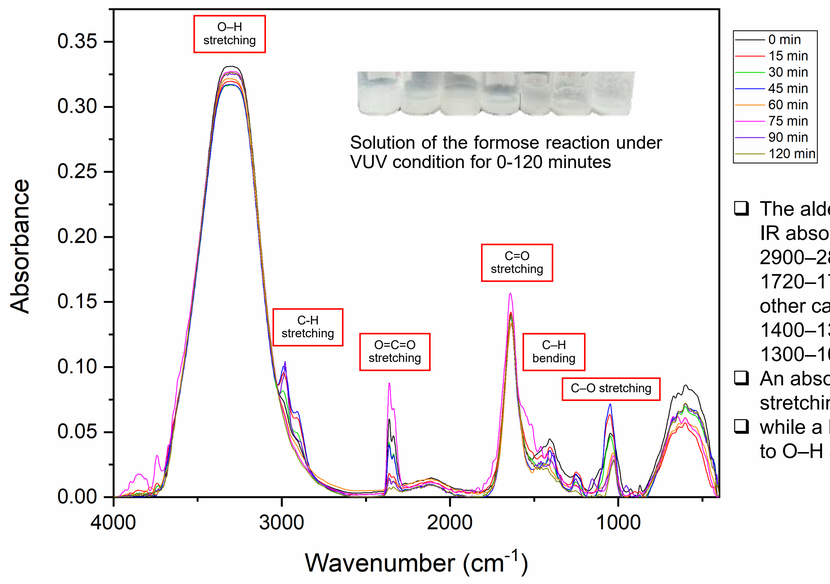
Thermal Conditions



- ❑ The aldehyde functional group shows characteristic IR absorptions as follows
  2900–2800 cm^{-1} (aldehydic C–H stretching)
  1720–1700 cm^{-1} (C=O stretching of aldehydes and other carbonyl compounds)
  1400–1300 cm^{-1} (C–H bending)
  1300–1000 cm^{-1} (C–O stretching)
- ❑ An absorption at 2349 cm^{-1} indicates CO_2 (O=C=O stretching)
- ❑ while a broad band at 3550–3200 cm^{-1} corresponds to O–H stretching in alcohols.

Figure 1 FTIR spectra of the formose reaction under thermal condition at 60 °C for 0-120 minutes

VUV Irradiation



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Figure 2 FTIR spectra of the formose reaction under VUV condition for 0-120 minutes

Fehling's test

Fehling's test showed a time-dependent formation of reducing sugars. The solution remained blue at 0 min, indicating a negative result. From 15–60 min, the formation of an orange to brick-red Cu_2O precipitate confirmed the presence of reducing aldehyde compounds.



The formation of an orange to brick-red Cu_2O precipitate indicates the presence of reducing aldehyde-containing compounds. A red precipitate was still observed at 90–120 min, indicating that reducing sugars were continuously present in the reaction system.

Conclusion

This study investigated the effect of Vacuum Ultraviolet (VUV) radiation on the formose-like reaction of formaldehyde under vacuum conditions. The results indicate that may promote the formation of reducing sugar-like compounds, as confirmed by the formation of brick-red Cu_2O precipitate in the Fehling's test. In comparison with thermal conditions, may enhance the formation of oxygen-containing organic compounds. The FTIR spectra obtained under both thermal (heat) and VUV irradiation conditions show the formation of oxygen-containing organic compounds from formaldehyde. In both conditions, a broad absorption band at 3200–3400 cm^{-1} corresponding to O–H stretching indicates the presence of hydroxyl groups, suggesting the formation of polyhydroxy compounds. Peaks observed around 2920–2850 cm^{-1} correspond to C–H stretching of aliphatic structures, while absorption bands in the 1200–1000 cm^{-1} region correspond to C–O stretching, which is characteristic of alcohols and carbohydrate-like molecules. However, the VUV irradiation condition shows more pronounced absorption peaks, particularly in the O–H and C–O regions, indicating a higher formation of polyhydroxylated organic compounds compared to the thermal condition. This suggests that VUV radiation provides sufficient energy to promote chemical reactions and enhance the formation of complex organic molecules through a formose-like reaction pathway.

These results indicate that VUV radiation plays an important role in promoting chemical reactions and possibly inducing radical formation, which enhances the formation of complex organic molecules through a formose-like reaction pathway. Overall, the findings demonstrate that the FTIR spectra under VUV irradiation show relatively stronger absorption in the O–H and C–O regions compared with the thermal condition. This observation suggests the formation of oxygen-containing organic compounds and may indicate enhanced formation of polyhydroxylated species.

References

[1] Omran et al. (2020) reported that the formose reaction produces complex mixtures of organic compounds derived from formaldehyde.
[2] The formose reaction can produce various sugar-like molecules from formaldehyde under alkaline conditions.
[3] From interstellar clouds to life. The sketch shows stages of evolution from molecular clouds to planets (from left to right). The figure was constructed following Caselli & Ceccarelli (2012).
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Acknowledgement

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