Impact Generation of Sugar Molecules and Survival of Glycolaldehyde

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Abstract

Glycolaldehyde (GLA), a two-carbon sugar precursor, has been detected in multiple regions in our galaxy and on comets in our solar system. Impact experiments conducted at the Experimental Impact Laboratory at NASA's Johnson Space Center have shown that samples of GLA and GLA mixed with montmorillonite clays can survive impact delivery in the pressure range of 4.5 GPa to 25 GPa. When extrapolated to amounts of GLA observed in the comae and in situ on the nucleus of individual comets and assuming a monotonic impact rate in the first billion years of solar system history, these experimental results show that up to 1023 kg of cometary GLA could have survived impact delivery, even if comets made up just 20% of the total impactor population. Substantial amounts of threose, erythrose, glycerol, glycolic acid, and ethylene glycol would also have been produced or delivered, depending on initial amounts and impact conditions. During the era of heavy bombardment (~4.2 to ~3.7 billion years ago), when life may have been developing on Earth, cometary impacts were likely prevalent throughout the solar system. They would have delivered these sugar molecules to Mars and to the icy moons of Jupiter and Saturn, providing additional intriguing evidence that biomolecules would have been abundant on these planetary bodies, too. The presence and availability of these biomolecules under the right conditions may have driven prebiotic chemical reactions that lead to, for example, ribose, the five-carbon sugar in RNA. In short, because experimental evidence shows that GLA survives impact, understanding impact delivery of biomolecules (in general, and including amino acids) may be important for answering questions about the origin of life as we know it. A diverse and wide-ranging approach that includes not only practices of investigation (i.e., experiments, observations, modeling) but also experiences and perspectives of the investigators, will be key to addressing the issues related to the origin of life on Earth and potentially elsewhere.

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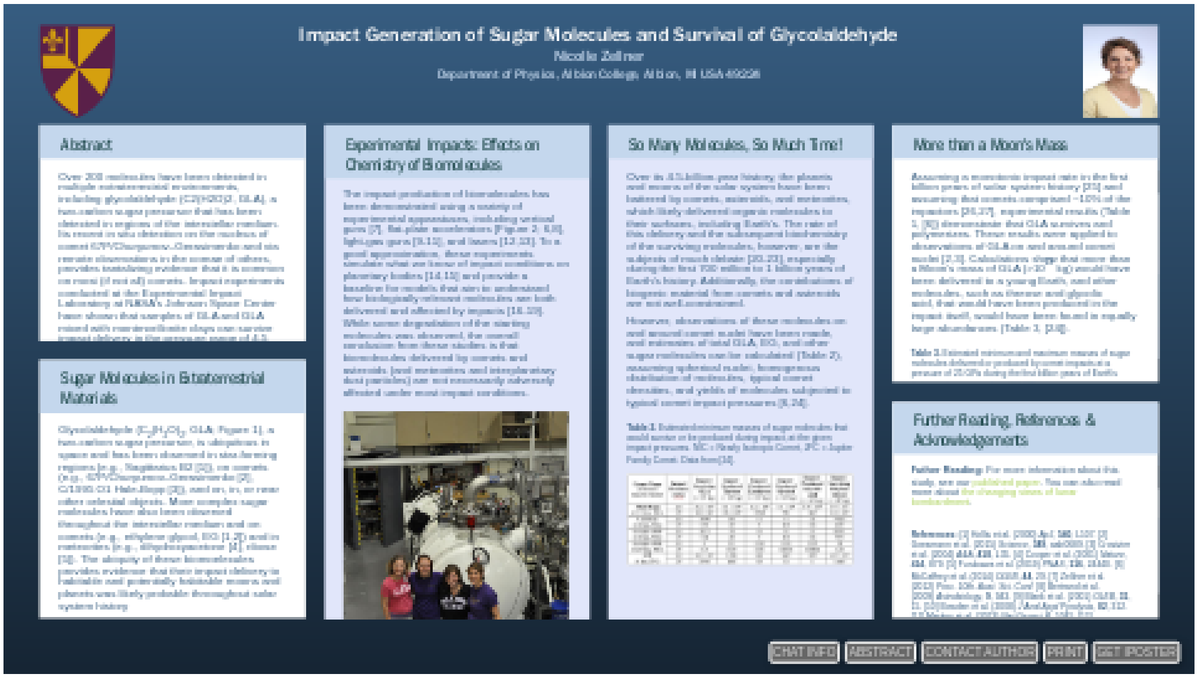

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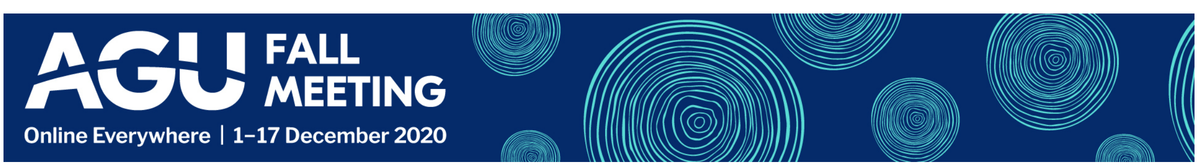

ABSTRACT

Over 200 molecules have been detected in multiple extraterrestrial environments, including glycolaldehyde (C2(H2O)2, GLA), a two-carbon sugar precursor that has been detected in regions of the interstellar medium. Its recent in situ detection on the nucleus of comet 67P/Churyumov–Gerasimenko and via remote observations in the comae of others, provides tantalizing evidence that it is common on most (if not all) comets. Impact experiments conducted at the Experimental Impact Laboratory at NASA's Johnson Space Center have shown that samples of GLA and GLA mixed with montmorillonite clays can survive impact delivery in the pressure range of 4.5 GPa to 25 GPa. Extrapolated to amounts of GLA observed on individual comets and assuming a monotonic impact rate in the first billion years of solar system history, these experimental results show that up to 1023 kg of cometary GLA could have survived impact delivery, with substantial amounts of threose, erythrose, glycolic acid, and ethylene glycol also produced or delivered. Importantly, independent of the profile of the impact flux in the early solar system, comet delivery of GLA would have provided (and may continue to provide) a reservoir of starting material for the formose reaction (to form ribose) and the Strecker reaction (to form amino acids). Thus, comets may have been important delivery vehicles for starting molecules necessary for life as we know it.

SUGAR MOLECULES IN EXTRATERRESTRIAL MATERIALS

Glycolaldehyde ($C_2(H_2O)_2$, GLA; Figure 1), a two-carbon sugar precursor, is ubiquitous in space and has been observed in star-forming regions (e.g., Sagittarius B2 [1]), on comets (e.g., 67P/Churyumov–Gerasimenko [2], C/1995 O1 Hale-Bopp [3]), and on, in, or near other celestial objects. More complex sugar molecules have also been observed throughout the interstellar medium and on comets (e.g., ethylene glycol, EG [1,2]) and in meteorites (e.g., dihydroxyacetone [4], ribose [5]). The ubiquity of these biomoelecules provides evidence that their impact delivery to habitable and potentially habitable moons and planets was likely probable throoughout solar system history

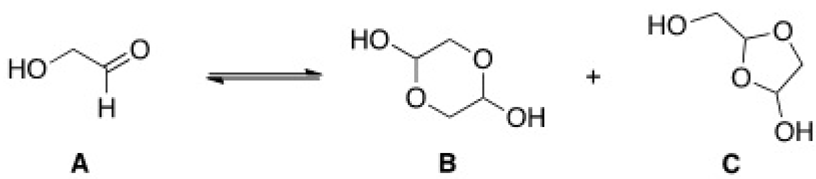

Figure 1. Structures of GLA monomer (A), 6-membered ring dimer (B), and 5- membered ring (C) dimer present in solution. [6].

EXPERIMENTAL IMPACTS: EFFECTS ON CHEMISTRY OF BIOMOLECULES

The impact production of biomolecules has been demonstrated using a variety of experimental apparatuses, including vertical guns [7], flat-plate accelerators [Figure 2; 6,8], light-gas guns [9-11], and lasers [12,13]. To a good approximation, these experiments simulate what we know of impact conditions on planetary bodies [14,15] and provide a baseline for models that aim to understand how biologically relevant molecules are both delivered and affected by impacts [16-19]. While some degradation of the starting molecules was observed, the overall conclusion from these studies is that biomolecules delivered by comets and asteroids (and meteorites and interplanetary dust particles) are not necessarily adversely affected under most impact conditions.

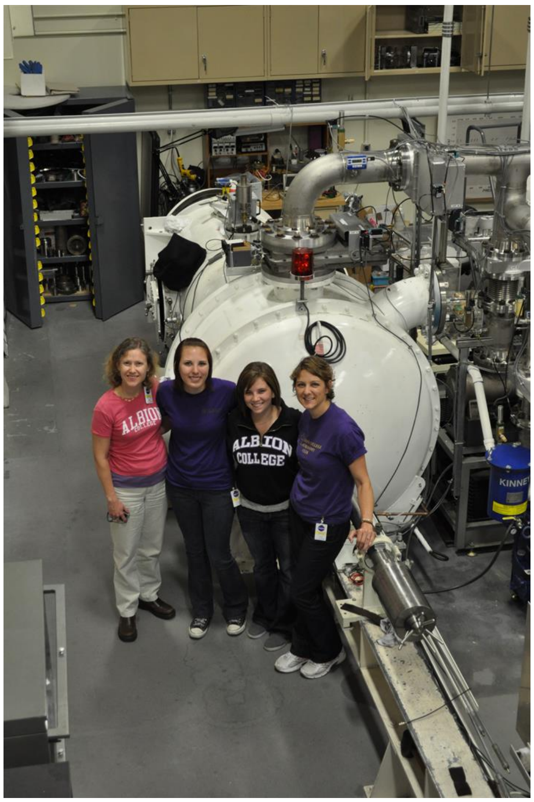

Figure 2. Running shock experiments at the Experimental Impact Laboratory at NASA Johnson Space Center.

As a direct application of how shock can affect the chemistry of GLA delivered by a comet, the dimerization reaction of GLA to produce the four-carbon sugars erythrose and threose was seen in the impact-shock experiments of GLA stabilized with montmorillonite clays [6]. McCaffrey et al. [6] showed that up to 95% of GLA can survive low-pressure impacts; that EG (a diol that is the reduced form of GLA) can be produced; and that erythrose and threose can be formed (Table 1).

Table 1. Results of impact experiments showing survival of GLA and production of threose, erythrose, ethylene glycol, glycolic acid, and glycerol under a variety of impact pressures. ND = not detected. Data are from [6].

	Unshocked GLA/Clay (1:20)	4.65 GPa	12 GPa	25.1 GPa
Percent Recovery of GLA	--	95%	96%	6.5%
Threose (all forms)	0.4%	3.6%	1.2%	1.2%
Erythrose	0.2%	0.6%	0.3%	0.2%
Ethylene Glycol	ND	ND	ND	0.5%
Glycolic Acid	0.62%	1.17%	0.62%	0.01%
Glycerol	0.16%	0.57%	0.30%	0.15%

SO MANY MOLECULES, SO MUCH TIME!

Over its 4.5-billion-year history, the planets and moons of the solar system have been battered by comets, asteroids, and meteorites, which likely delivered organic molecules to their surfaces, including Earth’s. The rate of this delivery and the subsequent biochemistry of the surviving molecules, however, are the subjects of much debate [20-23], especially during the first 700 million to 1 billion years of Earth’s history. Additionally, the contributions of biogenic material from comets and asteroids are not well-constrained.

However, observations of these molecules on and around comet nuclei have been made, and estimates of total GLA, EG, and other sugar molecules can be calculated (Table 2), assuming spherical nuclei, homogenous distribution of molecules, typical comet densities, and yields of molecules subjected to typical comet impact pressures [6,24].

Table 2. Estimated minimum masses of sugar molecules that would survive or be produced during impact, at the given impact pressures. NIC = Nearly Isotropic Comet, JFC = Jupiter Family Comet. Data from [24].

Comet Name (minimum diameter, family)	**Impact Pressure** (GPa)	**Impact-Surviving GLA** ($\times 10^6$ kg)	**Impact-Produced Threose** ($\times 10^6$ kg)	**Impact-Produced Erythrose** ($\times 10^6$ kg)	**Impact-Produced Glycerol** ($\times 10^6$ kg)	**Impact-Produced Glycolic Acid** ($\times 10^6$ kg)	**Impact-Surviving Ethylene Glycol** ($\times 10^6$ kg)
Hale-Bopp (13.5 km, NIC)	4.6	2.4×10^6	8.1×10^4	1.4×10^4	1.3×10^4	2.9×10^4	1.5×10^7
	25	1.6×10^5	2.8×10^4	3708	791	247	1.0×10^6
Lemmon (1.0 km, NIC)	4.6	1909	66	11	11	24	5920
	25	131	23	3	0.6	0.2	405
Lovejoy 2013 (1.0 km, NIC)	4.6	1671	58	10	10	21	8633
	25	114	20	3	0.6	0.2	591
Lovejoy 2014 (0.25 km, NIC)	4.6	4	0.1	0.02	0.02	0.05	18
	25	0.3	0.05	0.01	0.0013	0.0004	1.23
67P (4 km, JFC)	4.6	4.0×10^4	1392	241	229	495	2.0×10^4
	25	2750	486	63	14	4	1400

MORE THAN A MOON'S MASS

Assuming a monotonic impact rate in the first billion years of solar system history [25] and assuming that comets comprised ~10% of the impactors [26,27], experimental results (Table 1, [6]) demonstrate that GLA survives and polymerizes. These results were applied to observations of GLA on and around comet nuclei [2,3]. Calculations show that more than a Moon's mass of GLA (>10^{22} kg) would have been delivered to a young Earth, and other molecules, such as threose and glycolic acid, that would have been produced in the impact itself, would have been found in equally large abundances (Table 3, [24]).

Table 3. Estimated minimum and maximum masses of sugar molecules delivered or produced by comet impacts at a pressure of 25 GPa during the first billion years of Earth's history, using masses from [20,25].

	GLA (kg)	**Threose** (kg)	**Erythrose** (kg)	**Glycerol** (kg)	**Glycolic Acid** (kg)	**Ethylene Glycol** (kg)
Minimum	3.0×10^{16}	5.0×10^{15}	1.0×10^{15}	1.3×10^{14}	4.0×10^{13}	1.2×10^{17}
Maximum	1.6×10^{23}	2.8×10^{22}	3.7×10^{21}	7.9×10^{20}	2.5×10^{20}	1.0×10^{24}
67P (Maximum)	2.8×10^{21}	4.9×10^{20}	6.3×10^{19}	1.4×10^{19}	4.0×10^{18}	1.4×10^{21}

The survival of GLA and impact-production of other sugar molecules implies that reservoirs of this material would be available for the formose reaction (to make ribose) and Strecker synthesis (to make amino acids). A steady (though declining) flux of impacting comets over the first billion years of Earth's history implies an almost constant source of GLA. It is likely that Mars, Europa, and other potentially habitable planets and moons also experienced such deliveries.

FURTHER READING, REFERENCES & ACKNOWLEDGEMENTS

Futher Reading: For more information about this study, see our published paper (https://www.liebertpub.com/doi/full/10.1089/ast.2020.2216). You can also read more about the changing views of lunar bombardment (https://link.springer.com/article/10.1007%2Fs11084-017-9536-3).

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