Shock synthesis of complex macroscale structures in impacting mixture of amino acids and nucleobases - Pathways towards complexity. V S Surendra[1,*], V Jayaram[2], S Karthik[1], S Vijayan[1], V Chandrasekaran[3], R Thombre[4], T Vijay[5], B N Raja Sekhar[6], A Bhardwaj[1], G Jagadeesh[7], K P J Reddy[7], N J Mason[8], B Sivaraman[1,*], [1]Physical Research Laboratory, Ahmedabad, India,[2]Indian Institute of Science, Bangalore, India,[3]Vellore Institute of Technology, Vellore, India,[4]Modern College of Arts and Science, Pune, India, [5]Indian Institute of Technology Gandhinagar, Gandhinagar, [6]BARC at RRCAT, Indore, India,[7]Indian Institute of Science, Bangalore, India, [8]University of Kent, United Kingdom. **Email: surendra@prl.res.in, bhala@prl.res.in*

Introduction Impacts are ubiquitous in the Solar System. Impacts induced shock creates a high temperature and pressure which provides sufficient energy to overcome the thermochemical barrier for different chemical pathways enabling large scale molecular synthesis. With increasing evidence of impact history over Solar System bodies, impact-shock could be a profound source for the synthesis of complex molecules on the Solar System bodies. However, such impacts and the impact associated shock processing of molecules in extreme conditions largely remains unexplored. Previous studies have shown that the building blocks of life such as amino acids can be synthesized by such a process [1,2], which is the first crucial step for the origins of life. It is therefore necessary to understand the fate of such prebiotics in those extreme conditions. Blank et al. [3], performed impact experiments on an aqueous solution of amino acids at room temperature and observed signatures suggesting formation of peptides observations also reported by Sugahara and Mimura [4] who performed impact experiments under cryogenic conditions. Here, we report laboratory synthesis of complex macroscale structures in simulated shock conditions utilizing a shock tube. To the best of our knowledge, this is the first report on the formation of the complex structure by shock condition.

Experimental set-up: To simulate impact shock conditions, we employed a 7-meter-long, gas-driven shock tube with the driven side first pumped down to 10^{-4} mbar to avoid any contamination of gases and then purged with argon up to low pressure (~ 0.1 bar). The driver section of the shock tube was also pumped down to 0.01 bar and then filled with high pressure (40-60 bar) helium gas to burst an aluminum diaphragm of 1.5-2 mm thickness which is mounted between driver section and driven section. Samples were loaded on a sample holder mounted in a reaction chamber at the end of the driver section. Sudden bursting of diaphragm results in the formation of shock waves which propagate through the driven section and interact with the sample in the reaction chamber. A series of shock experiments were conducted with various mixtures of amino acids and nucleobases with the shock estimated to create a temperature range between 1500 and 8000 K [5]. The temperature-pressure values are calculated using one-dimensional normal shock equations known as R-H relations. After shock processing samples were taken out from reaction chamber and stored in inert conditions . The samples were then characterized using Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM).

Results: Samples before shock and aftershock were subjected to SEM and TEM analysis, The un-shocked sample does not show any specific patterns (Fig. 1a), while the shocked samples show the formation of complex macroscale structures. The most prominent features that are observed are threads with the length of a few 10's of micrometers to mm. We also observed certain geometric structures, zig-zag rods, ribbons with a smooth texture, twisted threads. On increasing the combination mixture of amino acids, we observed more complex structures. While adding glutamic acid to glycine, a bunch of flower petals appeared. With the further addition of two more amino acids, we observed

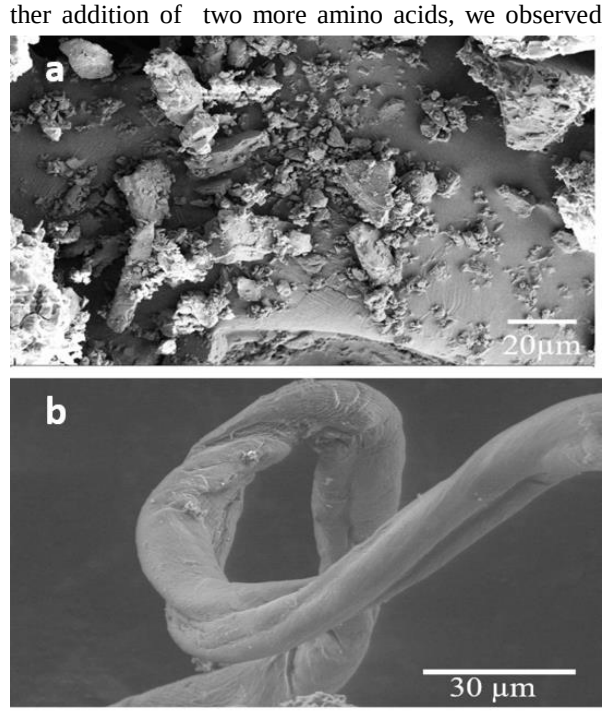

Fig.1. SEM micrograph of (a) powder samples (sizes ~ 20 µm) of 18 amino acid mixture before shock and (b) structured thread feature, more than 100 µm long, after shock processing.

the cylindrical tubes with complex patterns. With a mixture of amino acids a complex structure containing tubes, folded and twisted threads was observed (Fig.

1b). Similar patterns were also observed with nucleobases and other amino acid mixtures. TEM analysis also suggests that structures like spongy sheets, nanofibers are present.

Discussion: Our experiment provides compelling evidence of a synthetic pathway for complex macroscale structures due to the shock processing of biomolecules. The results are clear evidence for the assembly of bio-molecules in simulated impact–shock condition and play a significant step towards our understanding of the origins of life. Given the plethora of Solar System bodies with the necessary composition, impact-shock could have acted as a driving force to form more complex assemblies. Furthermore, our experiment could also be a possible explanation for the thread-like features reported in the meteorites [6], which were initially suggested to be a fossilized life form, but which could be the aggregation of biomolecules that have been shock processed during impact events. Further experimental being conducted which we hope will enhance our understanding in this field.

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