

Day 2 & 3, Wednesday, 31.8. & Thursday, 1.9.2022

Table of Content: Session 3 Talks

KEYNOTE

Dew RNA world: starting evolution from the solid state

Dieter Braun¹

¹LMU München

11 Prebiotic chemistry networks for carbon fixation and joining building blocks

Liu Z¹

¹MRC - Laboratory Of Molecular Biology

20 Heterogeneous Reactants at the Origin of Life: Towards Prebiotically Plausible Nonenzymatic RNA Copying

Duzdevich D¹, Carr C², Zhang S¹, Szostak J¹

¹Harvard University, ²Georgia Institute of Technology

990 An analysis of nucleotide-amyloid interactions reveals binding to codon-sized RNA

Saroj K. Rout, Anna Knörlein, Jonathan Hall, Jason Greenwald and Roland Riek

¹ETH Zurich

34 Photochemical Reactions in Lakes on Early Earth

Kufner C¹, Lozano G¹, Mast C², Zinth W², Braun D², Ranjan S³, Todd Z⁴, Sasselov D¹

¹Harvard University, ²Ludwig-Maximilians-University, ³Northwestern University, ⁴University of Washington

36 Impact of radioactive potassium on the emergent molecular structures of terrestrial life

Vladilo G¹

¹INAF - Osservatorio Astronomico di Trieste

42 Meteorite Impacts and the Emergence of Life

Sapers H¹, Cockell C³, Osinski G², Pontefract A²

¹York University, ²The University of Western Ontario, ³University of Edinburgh

49 Formation rates of ferrocyanide on the early Earth and their implications for prebiotic chemistry

Todd Z¹, Catling D¹

¹University Of Washington

54 Non-enzymatic templated ligation of oligonucleotides containing 2',3' cyclic phosphate

Wunnava Venkata S¹, Serrão A

¹LMU Munich CeNS

59 Consideration on the role of coenzymes in the evolution of Life

Kirschning A¹

¹Leibniz University Hannover

Poster Session 3

6 Prebiotic vesicles on a cold early Earth could have encapsulated solutes, and grown by micelle addition after brief cooling below the membrane melting temperature

Cohen Z¹, Todd Z¹, Catling D¹, Black R¹, Keller S¹

¹University of Washington

15 Heat flows as a prebiotic driving force of a natural origin-of-life-laboratory

Mast C¹

¹Lmu

16 Coexistence and evolution of replicators in Metabolically Coupled Replicator Systems (MCRS)

Konnyu B¹

¹Centre for Ecological Research

17 Meteorites and the RNA World: Synthesis of Nucleobases and Ribose in Carbonaceous Planetesimals

Paschek K¹, Semenov D^{1,2}, Pearce B^{3,4}, Lange K⁵, Kohler K^{2,1}, Henning T¹, Pudritz R^{3,4}, Trapp O²

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22 An Amyloid-Centric View of the Prebiotic Origin of Molecular Complexity

Rout S¹, Bomba R¹, Kwiatkowski W¹, Greenwald J¹, Riek R¹

¹Laboratory of Physical Chemistry, ETH Zurich

28 Quantum Mechanical Exploration of Prebiotic Chemical Reaction Networks

Weymuth T¹, Reiher M¹

¹Laboratory of Physical Chemistry, ETH Zurich

31 Stereoselective Peptide Catalysis in Complex Environments – From River Water to Cell Lysates [1]

Rackl J¹, Schnitzer T¹, Wennemers H¹

¹ETH Zurich

38 Si isotopes of microbially induced clay minerals: Exploring a new biosignature for the search for life on Mars

Cellino L¹, de Souza G¹, Bontognali T^{3,4}, Galili N², Hemingway J², Vance D¹

¹Institute of Geochemistry and Petrology, Department of Earth Sciences, ETH Zürich, ²Institute of Geology, Department of Earth Sciences, ETH Zürich, ³Space Exploration Institute, ⁴University of Basel, Department of Environmental Sciences

47 The Marslabor of the University of Basel: Acquiring close-up images of geological samples in view of the ExoMars rover mission

Bontognali T^{1,2}, Ligeza G², Kuhn B², Josset J¹, Hofmann B^{3,4}, Kuhn N²

¹Space Exploration Institute, ²University of Basel, ³Natural History Museum Bern, ⁴University of Bern

55 Emergence of structure in oligomers originating from templated polymerization of biased pools

Calaça Serrão A, Dänekamp F, Braun D

¹LMU Munich

56 Heat flows shift chemical equilibria by selective accumulation of ions

Matreux T¹, Aikkila P¹, Schmid A¹, Le Vay K³, Raith J², Kühnlein A¹, Weller D⁴, Rappold M¹, Dingwell D⁴, Altaner B², Guyot F⁵, Gerland U², Scheu B⁴, Mutschler H³, Braun D¹, Mast C¹

¹Systems Biophysics, LMU Munich, ²Physics of Complex Biosystems, TU Munich, ³Biomimetic systems, TU Dortmund, ⁴Earth and Environmental Sciences, LMU Munich, ⁵Muséum National d'Histoire Naturelle

65 Short peptide amyloids are likely a sequence pool for emergent proteins.

Kwiatkowski W¹, Greenwald J¹, Riek R¹

¹ETH

68 The surface chemistry of oxides: catalytic activation of the small molecules point of view

Yakimov A¹, Copéret C¹

¹ETH Zurich

Session 3

Talks

KEYNOTE

Dew RNA world: starting evolution from the solid state

Dieter Braun¹

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Understanding the emergence of life means to recreate a physico-chemical system that is capable of open ended Darwinian evolution. The more simple it is and the less special compounds and conditions it require, the more probably it can occur. We will discuss experiments that imply a fundamentally simplified RNA world that starts from the solid state.

We revisited polymerization and templated ligation of RNA from nucleotides with 2',3' cyclic phosphates. They oligomerized under alkaline conditions at pH 9-11 without catalysts or added salts, reaching 10 mers in a day, both in the 'dry' state or in the wet-dry cycling at a heated air-water interface [1]. At high temperatures, the oligomers were dominated by G, but cold and dry conditions, achieved in the planet simulator of McMaster University, yielded random sequences of GC or GCAU. The yield for oligonucleotides which contain still a functional 2'3'-phosphate peaks between 4°C and 25°C.

Under similar conditions, phosphorylation from Trimetaphosphate and templated ligation was observed under such "dry" conditions. We envisage therefore a one pot reaction from nucleosides to the replication of oligomers. The separation of strands would be provided by the condensation of salt-free dew droplets which also dissolve new feeding nucleosides from the solid state, triggering another cycle of phosphorylation, polymerization and templated ligation in the "dry" state. A likely driving for this mechanism would be the day night cycles. We are searching for short RNA sequences to enhance this replication by ligation in the dry state, leading to a much simplified RNA world to trigger self-amplified biological evolution of functional sequences.

In deeper layers of the porous rock, we envisage that air-water interfaces drive more sophisticated Ribozymes. We shown that CO₂-water interfaces can drive the replication towards sequence lengths of up to 1300 mers, overcoming the tyranny of the shortest by the length selective accumulation under evaporation-based capillary flow. The long strands separate under the pH and salt cycling provided by the Hadean atmosphere of CO₂. While the replication was still implemented by a polymerase to enhance kinetics, preliminary results show a similar strand separation for Ribozymes under elevated Mg²⁺ concentrations.

[1] doi:10.26434/chemrxiv-2022-zwh2t (2022)

[2] Nature Physics doi.org/10.1038/s41567-022-01516-z (2022)

14:10 – 14:30

11

Prebiotic chemistry networks for carbon fixation and joining building blocks

Liu Z¹

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Life is an out-of-equilibrium system sustained by a continuous supply of energy. In extant biology, the generation of the primary energy currency, adenosine 5'-triphosphate and its use in the synthesis of biomolecules require enzymes. Before their emergence, alternative energy sources, perhaps assisted by simple catalysts, must have mediated the prebiotic chemistry reactions. Here I will present two examples for these prebiotic chemistry reaction networks. Firstly, we demonstrate an efficient ultraviolet photoredox chemistry between CO₂ and sulfite that generates organics and sulfate. The chemistry is initiated by electron photodetachment from sulfite to give sulfite radicals and hydrated electrons, which reduce CO₂ to its radical anion. A network of reactions that generates citrate, malate, succinate and tartrate by irradiation of glycolate in the presence of sulfite was also revealed. The simplicity of this carboxysulfitic chemistry and the widespread occurrence and abundance of its feedstocks suggest that it could have readily taken place on the surfaces of rocky planets. The availability of the carboxylate products on early Earth could have driven the development of central carbon metabolism before the advent of biological CO₂ fixation. Secondly, I will talk about that the chemical energy inherent to isonitriles can be harnessed to activate nucleoside phosphates and carboxylic acids through catalysis by acid and 4,5-dicyanoimidazole under mild aqueous conditions. Simultaneous activation of carboxylates and phosphates provides multiple pathways for the generation of reactive intermediates, including mixed carboxylic acid–phosphoric acid anhydrides, for the synthesis of peptidyl–RNAs, peptides, RNA oligomers and primordial phospholipids.

14:30 – 14:50

20

Heterogeneous Reactants at the Origin of Life: Towards Prebiotically Plausible Nonenzymatic RNA Copying

Duzdevich D¹, Carr C², Zhang S¹, Szostak J¹

¹Harvard University, ²Georgia Institute of Technology

The RNA World hypothesis posits that RNA played an essential role during the origin of life by serving as both the hereditary material, and the primary molecule of function in the form of ribozymes. The Szostak laboratory uses model systems to experimentally study how primitive forms of RNA propagation may have emerged in the absence of enzymes. A key step on the pathway to achieving nonenzymatic RNA replication is nonenzymatic template-directed nucleotide polymerization. Experiments in this field typically employ defined or homogenous template sequences and one or only a few chemically activated nucleotide species (for example, a poly-rG template and rC reactants). A more realistic scenario is to consider random templates and all four canonical nucleotide reactants. We recently developed a sequencing assay that has enabled us to characterize this scenario for the first time. We were especially interested in understanding the origin of mismatches, which are much more common without the work of enzymatic regulation, and found that correct copying in our system depends on the prevalence of a previously-identified 5'-5' bridged dinucleotide reactant.

We are adapting this assay to consider progressively more realistic scenarios. First, we have incorporated a prebiotically plausible methyl isocyanide-based nucleotide activation chemistry (instead of using artificially-activated and purified reactants). This approach improves reaction fidelity because the activation chemistry drives the formation of the bridged dinucleotide, thereby increasing the probability of correct incorporations. Second, we are introducing greater heterogeneity among reactants by including various sets of short oligonucleotides. Previous work with defined sequences has shown that oligos can facilitate copying, but here we consider whether those improvements apply in a random-sequence context, and also whether the oligos benefit copying fidelity. Preliminary results suggest that these more realistic conditions can improve nonenzymatic copying, indicating that future work should embrace the heterogeneous conditions that would have prevailed during the emergence of life.

14:50 – 15:10

990

An analysis of nucleotide-amyloid interactions reveals binding to codon-sized RNA

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Interactions between RNA and proteins are the cornerstone of many important biological processes from transcription and translation to gene regulation, yet little is known about the ancient origin of said interactions. We have hypothesized that peptide amyloids played a role in the origin of life and that their repetitive structure lends itself to building interfaces with other polymers through avidity. Here we report that short RNA with a minimum length of three nucleotides bind in a sequence-dependent manner to peptide amyloids. The 3'-5' linked RNA backbone appears to be well-suited to support these interactions with the phosphodiester backbone and nucleobases both contributing to the affinity. Sequence specific RNA-peptide interactions of the kind identified here may provide a path to understanding one of the great mysteries rooted in the origin of life: the origin of the genetic code.

15:45 – 16:05

34

Photochemical Reactions in Lakes on Early Earth

Kufner C¹, Lozano G¹, Mast C², Zinth W², Braun D², Ranjan S³, Todd Z⁴, Sasselov D¹

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On the surface of the Early Earth, ultraviolet (UV) light is a key energy source for the formation of the building blocks of life.[1] However, it has remained an open question how deep UV light could have penetrated into natural waters on Early Earth or comparable exoplanetary systems. We studied the UV absorption spectra of a variety of salts available on Early Earth in the prebiotically abundant wavelength range between 200 nm to 360 nm.[2] As a result, we found wavelength dependent penetration depth. For all salts studied, we obtained low penetration depths for wavelengths around 200 nm and deeper penetration for longer wavelengths. Depending on their wavelength, the photons in the ultraviolet range between 200 nm and 360 nm can trigger a variety of photochemical reactions in prebiotic molecules: The absorption of a photon below 250 nm can eject solvated electrons from sulfite into the solution which have been shown to be essential to trigger reductive photochemistry[3] underneath the surface of prebiotic lakes. Photons with wavelengths up to 290 nm can induce sequence selective processes on short nucleic acids at higher depths. Nucleic acids strands can be destroyed photochemically in a sequence-dependent manner, yielding a selection of early sequences which could have formed the first proto-genomes. We determined the 266 nm UV stability of short DNA single strands, which consist of a random sequence of 8 bases in a massively parallel approach by next-generation sequencing.[4] Our findings strongly indicate that the UV stability of sequences could have influenced the development of codon/anticodon pairs in the evolution of life.

[1] a) M. W. Powner, B. Gerland, J. D. Sutherland, *Nature* 2009, 459, 239–242; b) J. Xu, N. J. Green, D. A. Russell, Z. Liu, J. D. Sutherland, *J. Am. Chem. Soc.* 2021, 143, 14482-14486; c) S. Ranjan, R. Wordsworth, D. D. Sasselov, *The Astrophysical Journal* 2017, 843, 110.

[2] S. Ranjan, C. L. Kufner, G. G. Lozano, Z. R. Todd, A. Haseki, D. D. Sasselov, *Astrobiology* 2022, 22, 242-262.

[3] Z. Liu, L.-F. Wu, C. L. Kufner, D. D. Sasselov, W. W. Fischer, J. D. Sutherland, *Nature Chemistry* 2021, 13, 1126-1132.

[4] C. L. Kufner, S. Krebs, M. Fischaleck, J. Philippou-Massier, H. Blum, D. B. Bucher, D. Braun, W. Zinth, C. B. Mast, Manuscript in preparation 2022.

16:05 – 16:24

36

Impact of radioactive potassium on the emergent molecular structures of terrestrial life

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Natural radionuclides are often considered as potential actors in the general scenario of prebiotic chemistry. Most of the studies driven by this idea have examined the radiochemical impact induced by the unstable isotopes of uranium and thorium. These heavy isotopes could play a role in the early prebiotic stages, but their decay products (alpha particles and unstable nuclei) would severely damage the key molecular structures that are expected to emerge at later stages (e.g., replicating and/or catalytic molecules). In this presentation I will examine a different radionuclide, the potassium isotope ⁴⁰K, and its decay products (mostly beta particles and stable nuclei) that have a milder radiochemical impact. Potassium is abundant and widespread in the Earth crust and oceans, whereas uranium and thorium are rare and concentrated in specific niches. Therefore, potassium (including its unstable isotope) was likely to be present in prebiotic chemistry, starting from the very earliest stages. Moreover, assuming continuity with extant biology, potassium (including its unstable isotope) was probably incorporated in the earliest, fully developed terrestrial cells. Based on these arguments, ⁴⁰K was likely to be present in all the prebiotic stages and, with a proper flux of decaying particles, may have influenced the molecular evolution leading to the emergence of life. The fact that the isotopic ratio ⁴⁰K/K was one order of magnitude higher than today when terrestrial life was born (early Archean) supports this possibility. For plausible values of potassium concentration, the specific rate of ⁴⁰K decays in an Archean aqueous medium could have been two orders of magnitude higher than in present-day eukaryotic cells. Preliminary estimates of the potential prebiotic impact of the resulting flux of beta particles will be provided in my talk. Molecular structures may be affected depending on: (i) the possibility of accumulating radiochemical effects and (ii) the distance range over which the cooperation of intermolecular forces can propagate the effects of beta decays. In the final part of my presentation I will discuss a further reason for examining the case of ⁴⁰K, related to the origin of the homochirality of biological biomolecules. The potential link between homochirality and ⁴⁰K is the parity violation of the beta decay, as a result of which the spin component of the emitted fast electrons is always antiparallel to the direction of motion. By coupling their spin with that of the molecules encountered along their path, the beta particles may induce a chiral imprint in the molecular structures. Despite the large number of studies trying to link the origin of homochirality to physical processes, the effects of a persistent injection of beta particles in protobiological structures have never been examined. The origin of homochirality is an open question in studies of abiogenesis and the possible impact of ⁴⁰K decays in this context should be quantified. Future steps to be undertaken for casting light on this subject will be briefly summarized.

16:25 – 16:45

42

Meteorite Impacts and the Emergence of Life

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Impact structures on Earth are often overlooked from a biological perspective even though they are a fundamental process in planetary evolution – indeed – they are the most common geological feature in the Solar System. The increased frequency of large impacts early in the Earth's history, commensurate with the origin and early evolution of life, has led to two hypotheses: 1) impact events frustrated the emergence of life, and 2) the energy and geochemical products of impact events facilitated habitability. Proposing a paradigm shift from sporadic, biologically destructive events, we posit that periods of high impact flux early in planetary evolution drive planetary habitability and facilitate the emergence of life. The impact cratering process both generates the conditions conducive to the origin of life as well as creates varied habitats for life that persist for thousands to millions of years following the impact event. Impact cratering generates subaerial and submarine hydrothermal systems in varied geochemical settings resulting in a diverse suite of water-rock reactions including serpentinization. Shock-metamorphism during an impact event results in unique geological materials such as impact analogues for volcanic pumice rafts in splash pools that provide protective niches and vesicular voids lined with phyllosilicate minerals and other catalytic substrates allowing for the concentration of pre-biotic chemicals. The impact process itself delivers many of the ingredients thought to be important in the early development of planetary habitability and the emergence of life such as complex organics and the atmospheric generation of hydrogen cyanide. Transient impact-associated hydrological systems, and the geological products of shock metamorphism such as impact glass and shocked crystalline rock that provide unique endolithic and lithotrophic niches persist long after impact. This work does not contradict existing environments proposed for the origin of life on Earth, rather we present the impact crater and the cratering process as an alternative mechanism to create the previously proposed environments and conditions necessary for the emergence of life. The impact process does not rely on other active geological processes such as plate tectonics, or volcanism and as such, impact cratering is ubiquitous on rocky and icy bodies in the Solar System, independent of size, internal heating mechanisms, and distance from the Sun. Impact events therefore potentially represent a mechanism to generate habitability on other planets, satellites, and even asteroids throughout and beyond the Solar System with implications for not only understanding the emergence of life on Earth, but a parsimonious mechanism for the putative emergence of life on other rocky and icy bodies. The most striking example of impact-associated biospheres on Earth are in the subsurface. Arguably, the most compelling environment in which to search for life beyond Earth is in the subsurface of other potentially habitable Solar System bodies such as Mars. Impact structures thus comprise novel modern subsurface environments that provide unique opportunities to study extant subsurface life on Earth with implications in the development of planetary habitability and for the emergence of life on Earth and potential for life elsewhere in the Solar System.

1.9.2022

8:45 – 9:05

49

Formation rates of ferrocyanide on the early Earth and their implications for prebiotic chemistry

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Ferrocyanide, a potentially important compound for the origins of life, could have been present on the early Earth in various geochemical environments. In addition to being an important prebiotic ingredient itself (e.g. Xu et al. 2018), ferrocyanide could provide a mechanism for storing and stockpiling other prebiotic molecules, including cyanide (Sasselov et al. 2020). While previous studies have examined the conditions under which ferrocyanide formation is thermodynamically favored (Toner and Catling 2019), the kinetics of ferrocyanide formation remain an open question.

Here, we investigate the rate of formation and formation efficiency of ferrocyanide from solutions containing various concentrations of ferrous iron and hydrogen cyanide, under a range of pHs. We find that this reaction occurs on fairly short timescales, reaching completion on the order of minutes to hours. We further find that formation efficiency is significantly increased at more basic pHs.

The results have implications for understanding what concentrations of ferrocyanide are plausible, and furthermore, what timescales are relevant for ferrocyanide formation on the early Earth. By quantifying the rate of this reaction, we can further build up a model of prebiotic lake chemistry and determine implications for prebiotic chemistry on the early Earth. Given the potential importance of ferrocyanide as a source of stockpiling the prebiotically relevant molecule cyanide, these results are significant for understanding the robustness of prebiotic lake chemistry invoked under early Earth conditions.

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9:05 – 9:25

54

Non-enzymatic templated ligation of oligonucleotides containing 2',3' cyclic phosphate

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Replication of genetic information is a necessary step for the emergence of life. Recently, we showed that 2',3'-cyclic nucleotides can polymerize non-enzymatically under alkaline drying conditions. In the current work, we expand on that work to show that oligonucleotides with 2',3'-cyclic phosphate end can ligate on a complementary template. The reaction proceeds in alkaline pH 9-11 aqueous solutions with 1mM MgCl₂ at 25 °C. Under the optimum conditions the reaction yields ~ 20% of product at 24h at pH 10 and is possibly only limited by the hydrolysis of the 2'3' cyclic phosphate end. We also show the replication potential of this system by using small RNA fragments and one template where the product of the first templated ligation step acts as the template for the next, creating a ligation chain reaction.

9:25 9:45

59

Consideration on the role of coenzymes in the evolution of Life

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The evolution of coenzymes, or the impact of coenzymes on the origin of Life, is fundamental for understanding our own existence and yet, this topic is rarely discussed in contemporary science. Coenzymes are small molecules that occupy an elementary role with respect to chemical reactivity and selectivity when associated with a macromolecular template. They are essential for functional biocatalysis in all living organisms and act as currency to regulate many basic metabolic processes. Many coenzymes have a simple chemical structure and are often nucleotide-derived, which suggests that they may have co-existed with the emergence of RNA and may have played a pivotal role in early metabolism. Based on current theories on the prebiotic evolution which attempt to explain the emergence of privileged organic building blocks, on protometabolic networks such as the reversed TCA cycle and on established biosynthesis of coenzymes, plausible hypotheses on the early role of coenzymes and cofactors in the evolution of Life will be discussed.

References:

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2. A. Kirschning, The coenzyme/protein pair: A neglected "chicken and egg" problem with significance for the origin of life, *Nat. Prod. Rep.* 2021, 38, 993 - 1010.
3. A. Kirschning, On the evolutionary history of the twenty encoded amino acids, *Chem. Eur. J.* 2022 accepted.

Posters Session 3

6

Prebiotic vesicles on a cold early Earth could have encapsulated solutes, and grown by micelle addition after brief cooling below the membrane melting temperature

Cohen Z¹, Todd Z¹, Catling D¹, Black R¹, Keller S¹

¹*University of Washington*

Replication of RNA genomes within membrane vesicles may have been a critical step in the development of protocells on the early Earth. Cold temperatures near 0°C improve the stability of RNA and allow efficient copying, leading some researchers to suggest that the first protocells arose in cold-temperature environments. However, at these temperatures, fatty acids (which would have been available on the early Earth) form gel phase membranes that are rigid and restrict mobility within the bilayer. Two primary roles of protocell membranes are to encapsulate solutes and to grow by incorporating additional fatty acids from the environment. Here we test whether fatty acid membranes in the gel phase accomplish these roles. We find that gel-phase membranes of 10-carbon amphiphiles near 0°C encapsulate aqueous dye molecules as efficiently as fluid-phase membranes do, but not after the aqueous solution is frozen (at -20°C). In contrast, gel-phase membranes do not grow by micelle addition. Growth resumes when membranes are warmed above the gel-liquid transition temperature. We find that longer, 12 carbon amphiphiles do not retain encapsulated contents near 0°C. Together, our results suggest that protocells could have developed within environments that experience temporary cooling below the membrane melting temperature, and that membranes composed of relatively short chain fatty acids would have had an advantage as temperatures approached 0°C.

Heat flows as a prebiotic driving force of a natural origin-of-life-laboratory

Mast C¹

¹*Lmu*

Prebiotic chemistry often requires certain ratios of ionic species to function. In natural environments, such as those created by the leaching of geomaterials, these requirements are difficult to meet. Examples are basaltic leaches, which contain more sodium than magnesium ions, inhibiting ribozyme function. Another problem is to bring sufficiently high phosphate concentrations, e.g. from apatite, into solution and to prevent its co-precipitation with calcium at non-acidic pH. A possible solution to these issues are lateral heat fluxes through thin, water-filled fractures such as those found in thermally stressed basaltic glass. This non-equilibrium process inverts both the concentration-ratio of sodium to magnesium and that of calcium to phosphate by the heat-driven convection of the solvent and the thermophoretic drift of dissolved ion which is strongly charge and size selective. We show that the excess magnesium thus produced allows ligase ribozymes to function. In the case of dissolved apatite, the thermophoretic separation of calcium and phosphate allows the phosphate to remain in solution even after pH neutralisation and to be concentrated over several orders of magnitude by further heat flow processes. This widely available and geologically plausible scenario could thus help to create the ionic conditions necessary for prebiotic chemistry.

Konnyu B¹¹*Centre for Ecological Research*

Metabolically Coupled Replicator Systems (MCRS) are a model-family in which a simple, physio-chemical and ecologically feasible scenario can be used to study the first steps of the emergence of early replicators communities and proto-cells. The basic idea of the MCRS is that replicators compete for monomers during their replication and, at the same time, replicators cooperate within a reaction network to catalyze their own monomers. During early evolution mineral surfaces created ideal circumstances for synthesis of longer replicators (e.g. RNAs) with three dimensional structure that correspondingly also might have had enzymatic activities. All replicators were in strong competition for monomers during the replication. Those replicators that supported somehow their own monomer supply (e.g. catalyzed a reactions in the monomer synthetic-pathway) might have created a replicator community with indirect interactions among them by the monomer supply and this community excluded all other replicators and communities that they were not so effective like that. All abstract and more realistic variants of the MCRS demonstrate that metabolically active replicators can maintain permanently and replicators are capable of evolving to develop more efficient communities. Furthermore the parasites of the system are not harmful but they are rather pre-adaptive member of the community as we show in this presentation.

Meteorites and the RNA World: Synthesis of Nucleobases and Ribose in Carbonaceous Planetesimals

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The origin of life might be sparked by the polymerization of the first RNA molecules in Darwinian ponds during wet-dry cycles. The nucleobases and the sugar ribose are key life-building blocks and were found in carbonaceous chondrites. Their exogenous delivery onto the Hadean Earth could be a crucial step toward the emergence of the RNA world. Here, we present the formation of these prebiotic organics through the Strecker synthesis and a simplified version of the formose reaction inside carbonaceous chondrite parent bodies. By using a coupled physico-chemical model, we calculate the abundance of these molecules within planetesimals of different sizes and heating histories. We perform laboratory experiments using catalysts present in carbonaceous chondrites to infer the yield of ribose among all pentoses forming during the formose reaction. These laboratory yields are used to tune our theoretical model that can only predict the total abundance of pentoses. We found that the calculated nucleobase and ribose abundances were similar to the ones measured in carbonaceous chondrites. In conclusion, the Strecker synthesis and aqueous formose reaction might produce most of these organics in carbonaceous chondrites. The life-building blocks of the RNA world could be synthesized inside parent bodies and later delivered onto the early Earth.

An Amyloid-Centric View of the Prebiotic Origin of Molecular Complexity

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The origin of life presents a series of conundrums, one of which is the question of how “prebiotic” molecules became organized into more complex systems of interacting molecules. We have been pursuing the hypothesis that simple peptide aggregates known as amyloids have inherent properties that can explain many questions regarding the origin of molecular complexity. Along the way, we have found that amyloids can chemically self-replicate and self-assemble inside of a protocell as well as specifically bind to codon-sized RNA molecules in a mutually stabilizing interaction.

Quantum Mechanical Exploration of Prebiotic Chemical Reaction Networks

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Exhaustive computational explorations of prebiotic chemical reaction networks are now within reach due to recent developments of automated quantum mechanical exploration software [1-4]. With our SCINE Chemoton [5,6] computer program, we are able to probe hypotheses of abiogenesis without the need to perform potentially complex and resource-intensive laboratory experiments. At the same time, we obtain detailed mechanistic and kinetic information about viable production (and decomposition) paths of biochemically relevant molecules. We can study whether and to what extent more complex molecules are formed from simpler building blocks, along which pathways they are formed, and whether they are stable in a given chemical environment [7-9].

Here, we present the SCINE Chemoton software for the automated exploration of chemical reaction networks and show first results for the exploration of two prototypic prebiotic systems, namely the formose network [6] and a Urey-Miller-type network starting from methane, ammonia, water, dihydrogen, and dinitrogen.

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Stereoselective Peptide Catalysis in Complex Environments –
From River Water to Cell Lysates [1]

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Peptides have been recognized as powerful catalysts for various reactions throughout the last two decades.[2],[3] Of these peptide catalysts, several are characterized by a high degree of stereoselectivity and reactivity. Similar to nature's catalysts, enzymes, they are also composed of amino acids but have a much lower molecular weight and could hence be considered 'mini-enzymes'. Whilst enzymes function splendidly at low concentrations in complex aqueous biological environments, peptide catalysts normally require pure organic solvents and high concentrations.[4a-h]

We were therefore intrigued by the question of whether a peptide catalyst could exhibit chemoselectivity in similar environments reminiscent of enzymes. Consequently, we probed the behavior of tripeptide catalysts in both hydrophobic and aqueous reaction media and further challenged the catalysts with complex reaction media, consisting of aqueous solutions, containing biomolecules, bearing functional groups that can coordinate or react with the catalyst, substrate, or intermediates. Finally, we subjected the peptide catalysts to the ultimate test by investigating their reactivity, chemoselectivity and stereoselectivity in cell lysate in micromolar concentrations, entering a range also typical for enzymes. Despite its relatively short length and small size, H-DPro- α MePro-Glu-NHC₁₂H₂₅ proved to be a conformationally well-defined tripeptide, able to catalyze C-C bond formations with high reactivity and stereoselectivity, independent of the solvent and its compound composition. In fact, this peptide yielded our desired product with excellent stereoselectivity ($\geq 93\%$ ee, d.r. 85:15 - 94:6) and yield (80 - 97%), even in cell lysate, a highly complex mixture with numerous compounds that could either react or coordinate to the catalyst, the substrates, or the reaction intermediates. These findings provoke the question of the potential role of peptide catalysis in nature and during the evolution of enzymes.

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Si isotopes of microbially induced clay minerals: Exploring a new biosignature for the search for life on Mars

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The 'Rosalind Franklin' rover of the ESA-led ExoMars mission will land on Mars with the goal of possibly finding evidence for the existence of extraterrestrial life. The rover will land at Oxia Planum, an area of Mars that has been selected as a promising site where to look for biosignatures. Indeed, orbital spectral analyses have shown the area to be rich in Fe- and Mg-rich phyllosilicates, matching spectra of smectite, vermiculite and saponite. The presence of these clays, which likely formed at low temperature in the presence of liquid water, points to the existence of a paleoenvironment that may have hosted microbial life. Moreover, experimental studies have shown that authigenic clay precipitation in an aqueous environment can be mediated by the presence of organic compounds and functional groups usually produced by living organisms. We have conducted a series of clay synthesis experiments aimed at expanding upon the organic compound-induced Mg-rich smectite synthesis carried out by Bontognali et al. (2014), with the aim of analyzing the Si stable isotope composition of the resulting silicate precipitates. Our hypothesis is that the presence of organic compounds during authigenic clay precipitation creates a kinetic fractionation of Si isotopes. Varying Si isotope signatures in the presence or absence of organic compounds could serve as a benchmark for the development of a new biosignature. Ultimately, this could be applied to Martian phyllosilicates – obtained from a future Mars sample return mission – in order to investigate the possibility of organic compounds being present upon their formation. This would have considerable implications for the search for life on Mars.

The Marslabor of the University of Basel: Acquiring close-up images of geological samples in view of the ExoMars rover mission

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The exploration of Mars may finally lead to find an answer to the fundamental question “Are we alone in the universe?”. Detecting any form of extant or extinct life on the Red Planet would provide key insight about the origin and distribution of life in the universe. Looking for signs of life on Mars is the main goal of the ESA-led ExoMars rover mission. Here, we describe the preliminary results of some ongoing mission-preparation activities, which are aimed at increasing the scientific return of one of the instruments that will be part of the rover payload, a close up imager called CLUPI. The instrument will be used to take high magnification images of rock textures and sedimentary structures. Such photographs will be of key importance to select interesting samples that will subsequently be analyzed by other instruments placed inside the rover, characterizing the mineralogy and, if present, detecting organic molecules. In view of the prime mission on Mars, we established an indoor facility – the Marslabor of the University of Basel – that has been built ad hoc for simulating a Martian landscape and a Martian illumination. By varying the working distance and light conditions it has been possible to perform an assessment of the minimal-working-distance required for interpreting rock textures and sedimentary structures that are potentially present at the landing site of the ExoMars rover (i.e., Oxia Planum). The collection of selected rocks includes early Archean microbially induced sedimentary structures (MISS) and other evaporitic minerals and clay-rich sediment that have a high potential of preserving biosignatures. The produced dataset will be of help to the science team for optimizing CLUPI and rover operations during the mission on Mars.

Emergence of structure in oligomers originating from templated polymerization of biased pools

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Whether and how structure emerges in random or semi-random nucleic acid pools is a central question in the origins of life. Previously, templated ligation of random AT binary DNA strands has been studied and was found to lead to a reduction of sequence space through selection mechanisms such as avoiding hairpin forming sequences and favoring of A rich and T rich sequences.

We studied polymerization of 12 nucleotides long DNA oligomers of random binary composition (AT or GC) in a model system with Bst enzyme and obtained product strands longer than 100 bp. Analysis of these products through next-generation sequencing revealed the emergence of sequence structure such as self-complementarity and zebreness for AT and favoring of bulky motifs for GC.

How initial composition affects sequence space diversity was investigated by using biased binary pools where the initial fraction of one nucleotide is skewed. Kinetics permitted to ascertain the dependence of length and structure on elongation mechanisms.

In the near future, an analysis of k-motif entropy and motif correlations should allow us to better understand the propagation of information within a sequence. It should also reveal at which scale traces of the initial sequence persist throughout the elongated sequence. This would enable us not only to observe the reduction of sequence space through polymerization, but also to identify possible mechanisms by which it is introduced.

Heat flows shift chemical equilibria by selective accumulation of ions

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The first steps in the emergence of life on Earth occurred on rocks and their constituent phases with a feedstock of simple molecules. Our aim is to combine this background with thermal non-equilibrium and bring together geomaterials, chemistry and microfluidics in a realistic environment.

Our experiments take place in reaction chambers, sandwiched between highly heat conducting sapphire plates that ensure complete thermal control including possible thermal gradients. Microfluidic structures are made from FEP, which lets us focus on the interactions between the molecules.

In this scenario, we see that ions leached from prebiotically plausible mineral samples are selectively accumulated by ubiquitous heat flows. Magnesium ions get enriched over Sodium ions and permit ribozyme activity [1]. Thermal non-equilibrium boundary conditions drive concentration gradients, generating and controlling pH gradients in a generally available setting.

Local gradients driven by heat fluxes offer unique opportunities to enable molecular selection on all levels: for simple salts, we see that Phosphate and Calcium are fractionated, making orthophosphate from Apatite available for chemical reactions even at neutral pH. For small organic molecules (such as nucleotides, RNA precursors and amino acids), we observe thermophoretic selectivity for a large pool of molecules (50+). Even for 1-atom differences and same masses, we find that heat flows can drive separation. For larger oligomers, they possibly drive evolution towards functional phenotypes at the origins of life.

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Short peptide amyloids are likely a sequence pool for emergent proteins.

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Our recent work has shown that amyloids can spontaneously form inside vesicles creating membrane enclosed complex structures of certain degree of variability. This is possible because fatty acids act as filters allowing passage of certain aminoacids and their activated form and as a barrier where aminoacids created from activated species or sequences of aminoacids synthesises inside are becoming non permeable and trapped in the vesicles. It is hypothesized that such preselected sequences become a sequence pool for the emergent proteins. During millions of years of evolution sequences in the current proteome diverged significantly from the original seeds but if the hypothesis is right we should see the trace of them in the current proteome. Here we show that if we find all 6,7,8,9-mers in the proteome and calculate their amyloidogenicity there are more amyloidogenic sequences in the current proteome than in the randomly created proteome of the same size. Moreover, there are more amyloidogenic sequences in archaea proteome than in primate proteome suggesting that the evolution of the proteome is towards a smaller number of amyloidogenic sequences.

The surface chemistry of oxides: catalytic activation of the small molecules point of view

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Activation and transformation of the small molecules, e.g. CO₂, CH₄, CH₃X and N₂, is challenging to their high stability under ambient earth conditions. In this context, our group and others have shown that the surfaces of oxide materials, e.g. alumina, aluminosilicates, that are ubiquitous on earth, can readily coordinate, activate and catalytically convert such small molecules under relatively mild conditions, in contrast to what may be observed in solution. This can originate from several possibilities: the presence of reactive centers on surface (sites with low coordination numbers, vacancies, frustrated Lewis acid pairs etc.) as well as thermodynamically driven adsorption, that enables a concentration increase of molecules at the surface, leading to a higher probability of reaction between them and increase kinetics.

While most of our research has been motivated by the fundamental understanding of the structure and reactivity of surfaces, in particular how C-C bonds can be formed on surfaces from C₁ molecules, one could easily imagine that these processes could be connected to the emergence of first organic molecules on earth and elsewhere.

In this contribution, we summarize the most prominent works of our group on the small molecules activation on the oxide surfaces. We address the structure of the reactive surface sites and the reaction intermediates observed by the state-of-the-art spectroscopic instrumental techniques. Finally, we demonstrate insights into the mechanisms of chemical transformations at the surface obtained using experimental evidences, further augmented by quantum chemical calculations.

As an example, the activation of the C-H bond in CH₄ was shown to occur on alumina and silica-alumina surfaces already in 1965 by means of indirect kinetic measurements using CD₄. With the development of spectroscopic techniques and quantum chemical calculations in last decades, we were able to show by combining in situ IR spectroscopy complemented by solid-state nuclear magnetic resonance (ss-NMR) spectroscopy and density functional theory (DFT) calculations that tri-coordinated aluminum sites are highly active for this reaction. We have later shown that such surface sites also convert dimethyl ether (CH₃OCH₃) into higher hydrocarbons. More recently, we have shown that highly isolated Cu(II) sites on alumina surfaces readily convert CH₄ into CH₃OH, paralleling what nature does using the respective mono-oxygenases.