Astrobiology

Biochemistry at a distance

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It is reputed that the discipline of astrobiology was a purely academic pursuit until, in a moment of insight inspired by a Martian meteorite, President Clinton undertook to fund the search for life in the universe. This initiative has thrived to become the NASA Astrobiology Institute (NAI) based at Ames, California. The first director, Nobel Laureate Dr Baruch Blumberg, was appointed in 1999. A Russian Astrobiology Centre has been established at St Petersburg, with parallel initiatives in Spain, Japan and Australia. The European Exo/Astrobiology Network Association (EANA), co-ordinated from Paris, held its inaugural meeting in 1999.

Astrobiology concerns how life arises and whether other planets could harbour life, both within our solar system and in other nearby systems. EANA defines it as "the study of the origins, early evolution, distribution and destiny of life"[1].

The NAI asks a series of questions[2]. How do habitable worlds form? How did living systems emerge? Can we recognize other biospheres? How do environmental changes affect emerging ecosystems? And, finally, what is the potential for biological evolution beyond the planet of origin? Answering these questions will involve cross-fertilization between multiple disciplines, ranging from planetary science to molecular biology.

Life elsewhere

This interdisciplinary ideal was illustrated at the EANA meeting 'Life in Extreme Environments' held at the Open University in 2004. Life, as we know it, must reside on planets. Stars are too hot and interstellar debris, too cold. Researchers are making efforts to catalogue stars with discernable planets. Within the current limits of technology, looking principally for fluctuations in trajectory or intensity, discoveries have been restricted to ultra-large (and very un-Earth-like) planets. So far this approach has been promising — planets have been detected around over 150 nearby stars.

Key words: astrobiology, biosignature molecules, evolution, Lomagundi-Jatulian event, Mars, Shunga Event.

Stellar wobbles and radiances have little to do with biochemistry, but many teams are gearing up to look for atmospheric signatures of life. This involves the spectroscopic search for oxygen, water and simple organic molecules, truly biochemistry at a distance. One specific example concerns the 'red edge', a sharp increase in leaf reflectance at between 700 and 750 nm and potentially a marker for extant vegetation on distant planets[3].

The success of recent Mars missions by NASA and the European Space Agency has provided compelling data for the presence of water on the planet, and earlier liquid water flows. This has heightened speculation that life evolved independently on Mars. Although probably much warmer at one time, the now hyper-cold Martian surface is difficult (and expensive) to investigate. As a surrogate, studies have been performed on extreme terrestrial environments, uncovering primitive micro-organisms that invade solid sandstone rocks at low temperatures, and insects that live their entire life at −18°C. Studies on sub-zero dry Antarctic valleys have revealed a surprising microbial diversity under conditions not dissimilar to past Martian environments[4].

The understanding of the emergence of life on Earth is of course a central thrust. The Earth and Moon formed approximately 4.5 Ga (billion, or 10^9, years) ago, and early life-forms are inferred for approximately 3.9 Ga ago, although recent DNA sequence data could argue for an emergence as early as 4.1 Ga ago[5]. Even so, researchers are beginning to realise the phenomenal rate of exchange of material between Mars and Earth.

Bacterial spores can survive for long periods in simulated space conditions and it has been calculated that over 10^{10} substantial fragments of surface rock have been ejected from the Earth by large meteor or bolide impacts over the last 4 Ga — and 0.01% of these are destined to reach the Martian surface in a time compatible with the transfer of bacteria. Conversely, over 0.5% of similar fragments lost from Mars eventually impact on Earth[6]. So if life evolved on either Mars or the Earth, it would in all likelihood have been liberally shared with other planets.

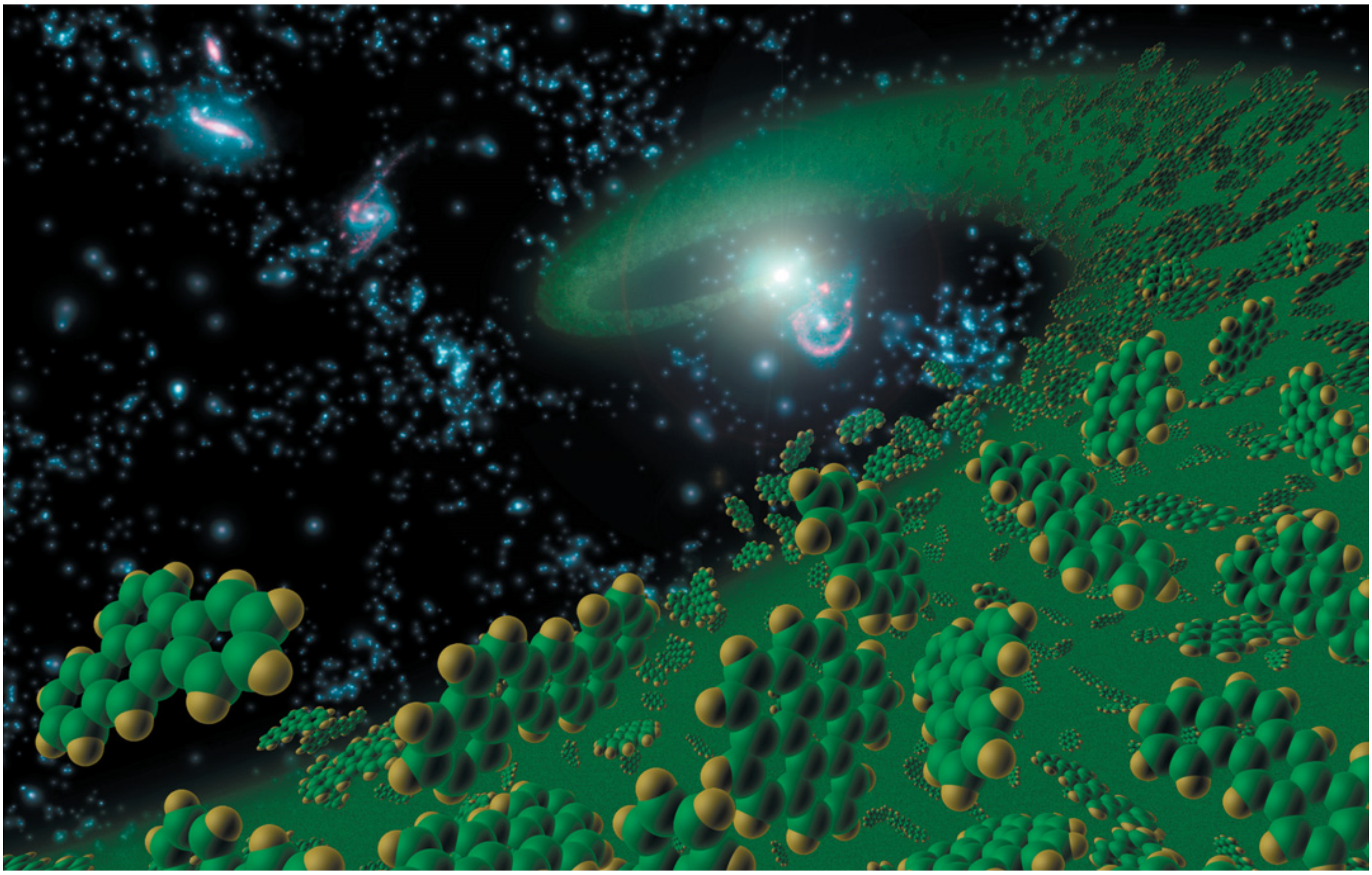

Figure 1: This artist's impression symbolically represents complex organic molecules including polycyclic aromatic hydrocarbons (PAHs) in the early universe. Two of three instruments aboard the NASA Spitzer Space Telescope are tuned to detect infrared fluorescence emissions characteristic of PAH molecules (5.8 to 8.0 micrometres) and provide clues to the abundance of potentially life-bearing chemicals in distant galaxies (www.spitzer.caltech.edu/features/articles/20050627.shtml). NASA/JPL-Caltech/T. Pyle (SSC)

Biochemical origin of life

One avenue of investigation is the simulation of early planetary conditions in the laboratory, a pastime associated with pioneers like Miller and Urey[7,8], but one which remains a major research focus. Non-enzymatic polymerization of nucleic acid precursors has been achieved in many laboratories, and some research groups find that the reaction is markedly stimulated by mineral surfaces, including clays[9]. So far, no one has offered an explanation of how primitive biopolymers such as DNA or RNA developed the capacity to code for polypeptides, and eventually came to be encapsulated in membranes to become cellular life.

A further problem concerns chirality: modern nucleic acids contain only D-sugars, whereas polypeptides only contain L-amino acids. Chemical reactions, in contrast, generate a precise 50:50 mix. The biochemical problem is that a growing polymer would be likely to randomly incorporate a mixture of D and L forms, leading to an unpredictable tertiary structure, most probably a dysfunctional product. Perhaps two separate chiral life forms evolved at the same time, only to resolve into the unique modern form through competition for resources[10]. An alternative view is that cellular life arose to solve precisely this problem.

Drilling through time: looking at the evidence

A major research area concerns the inspection of the earliest (Archaean) rocks on Earth for residua of early life. Blocks of ancestral crust have been identified, in Canada, South Africa and Australia, and three deep-drilling projects have been initiated: the Deep Time Drilling Project, in Australia; the Archean Biosphere Drilling Project (ABDP), also in Australia; and the Agouron Institute-sponsored drilling, in South Africa.

Deep Time has involved drilling

1 km cores through the Archaean–Proterozoic (~2.47–2.70 Ga ago) boundary, with a second investigation (500 m) through the earliest rocks of the Warrawoona and upper Coonterunah Groups (~3.45–3.52 Ga ago). The project aims to confirm the existence of Archaean hydrocarbon biomarker molecules, cited as evidence for the early existence of eukaryotes. Drilling took place in 2003.

ABDP involves research groups in Japan and Australia and aims to recover 'fresh' (unweathered) Archaean rocks (mostly sedimentary rocks 3.56–2.70 Ga in age) from the Pilbara district, Western Australia, and use them to address the distribution of organisms in the oceans, lakes and on land, the climate, and the chemical composition of the atmosphere and oceans. Drilling took place in 2004 and analysis is underway.

Drilling sponsored by the Agouron Institute during 2003 and 2004 recovered two parallel cores, each 1.5 km long, through the Campbellrand–Kuruman succession (~2.6–2.5 Ga ago) of South Africa. The goal is to establish the nature and distribution of organic biomarkers, palaeoclimate and ocean chemistry.

Biosignature molecules

Buried in these ancient rocks are molecules in organic sediments. Life is unusually selective in what molecules it forms — hydrocarbons are enriched in even-numbers of carbons (10, 12, 14) whereas odd numbers are depleted. L-Amino acids and D-sugars predominate. There are, however, concerns about the stability of these molecules over geologic time. Researchers have focused on 5-ring polycyclic hydrocarbons, the hopanes, that (like sterols in higher organisms, including plants) stabilize the bacterial cell membrane. These are very stable, and a distinctive cyanobacterial-type 2-methylhopanoid was extracted from an Australian shale dating to 2.5 Ga[11]. Andrew Steele, of the Carnegie Institution, is developing an automatic immunoaffinity detection device, a 'lab on a chip', targeting hopanes and related molecules, which is to be deployed on a future Mars mission. Work is needed to identify other biosignature molecules.

A period of massive change

A proposal co-ordinated by Victor Melezhik at the Geological Survey of Norway, outlined at a September 2005 International Continental Scientific Drilling Program (ICDP) workshop in Trondheim, seeks to address an equally critical period of the Earth's history[12].

Between 2 and 2.5 Ga ago, the Earth's surface underwent a series of huge upheavals and no one knows why. Before 2.5 Ga ago, the atmosphere was devoid of oxygen. Then, massive rifting and volcanic activity was followed by the earliest period of worldwide glaciation, enormous shifts in carbon isotope ratios at the so-called Lomagundi–Jatulian event, the oldest significant oil deposits (Shunga Event) and a huge rise in atmospheric oxygen.

Upheavals such as the K/T (Cretaceous/Tertiary) boundary (when the dinosaurs perished) are marked by isotope ratio changes, notably in the abundance of ^{13}C in carbonates. This is generally attributed to the kinetic isotope effect, where microbial enzyme reactions proceed more rapidly with the lighter ^{12}C and result in organic matter having lower levels of ^{13}C than contemporaneous marine (non-biological) carbonates.

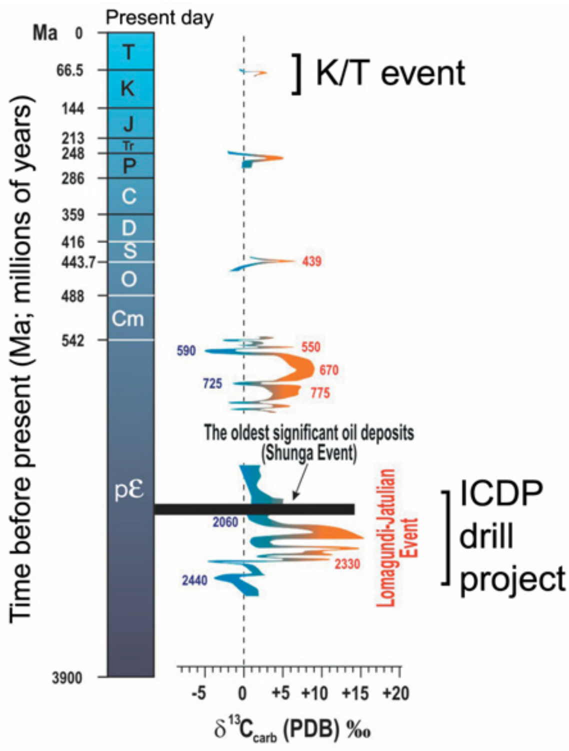

Figure 2. Major excursions in the $^{13}C_{carbonate}$ ratio through the Earth's history. The ^{13}C bias is expressed as parts per thousand (‰) against a fossil reference standard (PDB, Pee Dee belemnite). C, Carboniferous; Cm, Cambrian; D, Devonian; J, Jurassic; K, Cretaceous; O, Ordovician; P, Permian; pЄ, Precambrian; S, Silurian; T, Tertiary; Tr, Triassic; K/T refers to the bolide-impacting event at the Cretaceous–Tertiary boundary. Modified from Earth–Science Reviews, vol. **48**, Melezhik et al.[14], "Extreme $^{13}C_{carb}$ enrichment in ca. 2.0 Ga magnesite–stromatolite–dolomite–'red beds' association in a global context", pp. 71–120, ©1999, with permission from Elsevier and from Dr Melezhik.

Upheavals or reorganizations to the global carbon cycle that influence the burial ratio of carbonate to organic matter in sediments result in disturbances or excursions in the isotope ratios. In the time frame between 2 and 2.5 Ga ago there were huge ratio excursions that dwarf the minor and short-lived changes seen at the K/T event (Figure 2).

The excursions are positive, i.e. the sediments contain more ^{13}C than they should. When limestones and dolomites (calcium and magnesium carbonates) precipitate out of the ocean they capture whatever isotope ratio is present. The assumption is that life forms elsewhere on the planet have sequestered ^{12}C into organic deposits and the bias in abiotic carbonates reflects oceanic ^{13}C. The paradox is that there is so far no rock record of massive ^{12}C-enriched deposits during the Lomagundi–Jatulian event[13]: the standard explanation of the ^{13}C excursions may not be accurate.

Melezhik and colleagues are

proposing to harvest a series of deep drill-cores from the Fennoscandian Shield (northern Russia and Scandinavia) that will straddle key sedimentary strata from this period[12].

Lee Kump, from Pennsylvania State University's Astrobiology Research Center and a participant in the ICDP project, argues that the hike in atmospheric oxygen at this time is the most important event in the evolution of the modern biosphere and yet we know nothing about its origins.

Genomics specialists are considering the evolution and divergence of life, not only of particular species and genomes, but also of specific enzyme pathways. The surge of atmospheric oxygen must have required a specific evolutionary jump in microbial enzymology.

Was the oxygen rise a result of a shift in basic life organization and enzymatic processes, or did a chemical rise (produced perhaps by impacts or extraordinary volcanic activity) provide the trigger?

UK astrobiology

The UK Astrobiology Network was launched in 1999 at the request of the British National Space Centre (BNSC), accompanied by the first UK report on astrobiology. Growing out of this initiative, the Astrobiology Society of Britain (www.astrobiologysociety.org) was established in 2003, with the first UK astrobiology meeting held in Cambridge that year. The Royal Astronomical Society has an ongoing programme of workshops, many dedicated to astrobiology topics. More recently, an international meeting at the University of St Andrews, in May 2005, addressed the 'Origin, Evolution and Distribution of Life in the Universe'. The meeting brought together researchers across Scotland and the UK with recent research findings.

Now recognized as an academic discipline in its own right, an introductory course on the subject has been given at the Open University for some years. This academic year, the University of Glamorgan in Wales launched the UK's first undergraduate degree in astrobiology. And in Scotland, the Scottish Universities Physics Alliance has identified astrobiology as one of five main themes to promote for postgraduate-level study.

Biochemistry at a distance

Darwin and decades of molecular and biochemical research have yielded many insights into the events that accompanied the evolution of primitive vertebrates into fish, mice and humans. Some understanding of their finely evolved metabolic pathways has been achieved. The remaining goal, targeted by these astrobiology initiatives, is to understand the evolution of early microbial life and of the simplest life forms that preceded them —Dr Blumberg, the first NAI director, received his Nobel Prize for pioneering work in virology.

It may never be known if life in the solar system first evolved on Earth, Mars or even Europa, but the search for chemical biosignatures in the oldest terrestrial rocks (and on other planets) is hoped to cast light on the first emergence of life. And that principally means a modern laboratory set to analyse the data, where the techniques of classical biochemistry are likely to play a central role.

References

1. www.graz-astrobiology.oeaw.ac.at/eana.html
2. www.nai.arc.nasa.gov/
3. Seager, S., Turner, E.L., Schafer, J. and Ford, E.B. (2005) Astrobiology **5**, 372–390
4. Mahaney, W.C., Dohm, J.M., Baker, V.R. et al. (2001) Icarus **154**, 113–130
5. Battistuzzi, F.U., Feijao, A. and Hedges, S.B. (2004) BMC Evol. Biol. **4**, 44
6. Mileikowsky, C., Cucinotta, F., Wilson, J.W. et al. (2000) Icarus **145**, 391–427
7. Miller, S.L. (1953) Science **117**, 528–529
8. Miller, S.L. and Urey, H.C (1959) Science **130**, 245–251
9. Ferris, J.P., Hill, Jr, A., Liu, R. and Orgel, L.E. (1996) Nature (London) **381**, 59–61
10. Sandars, P.G.H. (2005) Int. J. Astrobiol. **4**, 49–61
11. Summons, R.E., Jahnke, L.L., Logan, G.A. and Hope, J.M. (1999) Nature (London) **400**, 554–557
12. www.icdp-online.de/sites/far-deep/objectives/objectives.html
13. Melezhik, V.A. and Fallick, A.E. (1996) Terra Nova **8**, 141–157
14. Melezhik, V.A., Fallick, A.E., Medvedev, P.V. and Makarikin, V.V. (1999) Earth–Sci. Rev. **48**, 71–120

Richard Lathe trained in Molecular Biology at Edinburgh and Brussels. After postdoctoral research in Heidelberg and Cambridge, he worked at the French Biotechnology company Transgene SA. More recently he has held Professorships at Strasbourg and Edinburgh. Currently director of a biotechnology consultancy, his diverse research interests include neuroscience and the chemical origin of life.

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Tony Prave gained his PhD in Geoscience from The Pennsylvania State University in 1986. He eschews labels but considers himself a field geologist interested in understanding Earth System evolution in Deep Time. His principal areas of research are the Precambrian rocks exposed in the deserts of Namibia and the American Southwest, as well as the wetter hills and dales of the Scottish–Irish Highlands and NW Russia.

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