Astrobiology and panspermia

Chandra Wickramasinghe (Cardiff University)

Darwin's allegorical 'warm little pond' was most probably located outside the Earth and Darwinian evolution, including genetic exchanges and transfers, occurred over a vast galactic scale.

Life from space

How did life arise? Not just on the Earth, but anywhere in the Universe? Does life emerge readily on every Earth-like planet by spontaneous processes involving well-attested laws of physics and chemistry, or did it involve an extraordinary, even miraculous intervention? Science must necessarily exclude a miraculous option of course, but the other questions continue to be asked.

Charles Darwin, the bicentenary of whose birth we celebrate this year, and who laid the foundations of evolutionary biology, never alluded to the origin of life in his 1859 book *On the Origin of Species*[1]. He had, however, thought about the problem and formulated his own position in a letter to Joseph Hooker in 1871 thus:

> **"….It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, &c., present, that a proteine compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly absorbed, which would not have been the case before living creatures were found."**

Darwin's prescient remarks provided the basic scientific framework for exploring the problem of abiogenesis throughout the 20th Century and beyond. In the late 1920s, A.I. Oparin[2] and J.B.S. Haldane[3] fleshed out Darwin's thoughts into the familiar 'Primordial Soup Theory', proposing that the atmosphere of the primitive Earth comprised of a reducing mixture of hydrogen, methane, ammonia and other compounds from which the monomers of life could be readily generated. Primitive 'lightening' and solar UV radiation provided the energy to dissociate these molecules, and the radicals so formed recombined through a cascade of chemical reactions to yield biochemical monomers such as amino acids, nucleotide bases and sugars. In the 1950s, the classic experiments of Harold Urey and Stanley Miller[4] demonstrated the feasibility of the Oparin–Haldane chemistry, and thus led to the belief that life could be generated *de novo* as soon as the biochemical monomers were in place. The formation of the first fully-functioning, self-replicating life system with the potential for Darwinian evolution still remains an elusive concept, however.

In recent years the fledgling science of astrobiology has taken up the challenge of extending the Oparin–Haldane ideas of abiogenesis to a wider cosmic canvas. This has been prompted in large measure by the discovery of biochemically relevant molecules such as polyaromatic hydrocarbons in interstellar space, an identification first reported in the journal *Nature* by Fred Hoyle and myself in 1977[5]. Such molecules have now been inferred to exist in vast quantity outside the confines of the Milky Way, extending even as far as a galaxy 8 billion light years away[6](Figure 1).

Figure 2 shows a part of a giant molecular cloud in the Orion Nebula of our own galaxy which is choc-a-bloc with PAHs (polycyclic aromatic hydrocarbons) and a wide range of other molecules, both organic and inorganic. Here is an active site of star-births, the youngest stars being younger than a few million years, and including many

Key words: *abiogenesis, astrobiology, Oparin–Haldane chemistry, panspermia, RNA world, Urey–Miller experiment*

nascent planetary systems (protoplanetary nebulae). This veritable stellar and planetary nursery is surely a region where a Urey–Miller experiment may be taking place on a grand cosmic scale. I shall argue as an alternative that it may also represent a graveyard of life — PAHs and other molecules present here arising from the destruction and degradation of life (see Figure1a).

It is generally conceded that the path from chemicals to self-replicating biology must progress through a sequence of organisational steps. The most popular contender for one such early stage is the RNA world. In this model, nucleotides polymerize into random RNA molecules that lead to autonomously self-replicating macromolecules (ribozymes) without the need for an intermediary enzyme[7,8]. Likewise, other contenders of prebiotic development include the 'iron–sulphur world'[9], the 'PNA (peptide nucleic acid) world'[10] and the 'clay world'[11], the latter involving an inorganic clay system serving as the informational template. In view of the high abundance of silicon in the galaxy, the clay world model might well have a special role to play in a cosmic context, as we shall see. The transition from any of these intermediate systems to the final DNA/protein-based cellular life form is still in the realm of speculation.

The difficulty of finding unequivocal evidence of the relics of prebiology in the geological record has been a handicap for Earth-based theories of the origin of life. The suite of organics present in interstellar clouds, as in Figure 2, consistently directs our search for origins away from Earth to more and more distant parts of the Universe. At the very least the organic molecules needed for life's origins are much more likely to have been generated in a cosmic context rather than being formed *in situ* on Earth. Moreover, it is now becoming clear that life arose on Earth almost at the very first moment that it could have survived. During the period from about 4.3–3.8 by ago (the Hadean Epoch), the Earth suffered an episode of heavy bombardment by comets and asteroids. Rocks dating back to the tail end of this epoch reveal evidence of an excess of the lighter isotope ^{12}C compared with ^{13}C pointing to the action of micro-organisms that preferentially take up the lighter isotope from the environment[12,13].

The success of the Urey–Miller experiment in 1953 led to the feeling that it was only a matter of time before the next steps from biochemical monomers to life could be demonstrated in the laboratory. Despite over half a century of effort, this goal has proved stubbornly elusive. If one accepts the calculations showing grotesquely small *a priori* probabilities for the transition of non-life to life[14–16],

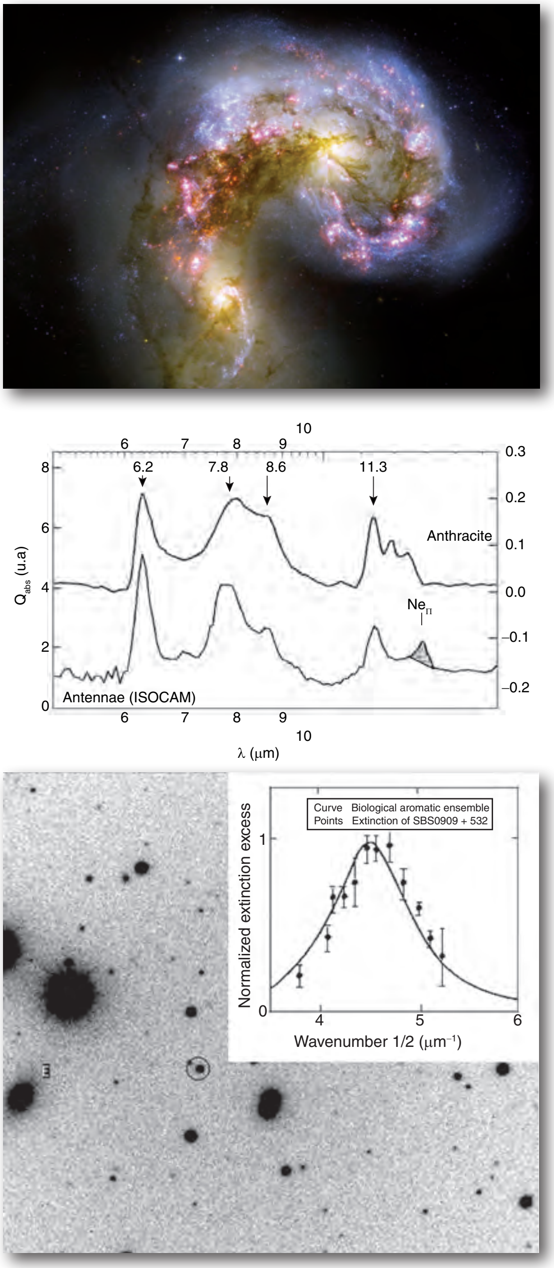

Figure 1. (**a**) At a distance of 63 million light years the Antennae galaxies show clear evidence of anthracite-like dust, consistent with a biological degradation product. (**b**) In the gravitational lens galaxy SBS0909+532, at a red-shift of z=0.83, corresponding to a distance of nearly 8 billion light years, a UV absorption signature centred on 2175Å consistent with biological aromatic polymers. A similar signature in dust of own galaxy was first attributed to biomaterial by Hoyle and Wickramasinghe in 1977[5]

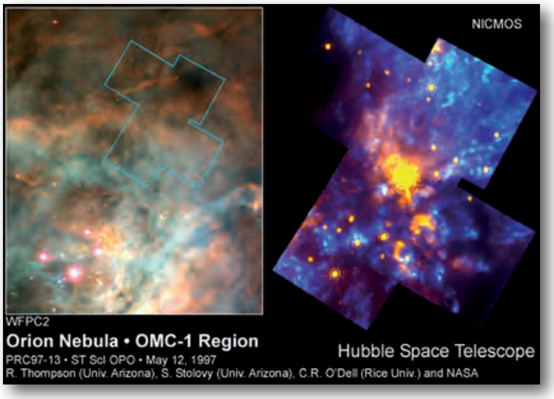

Figure 2. The Orion Nebula is a giant stellar and planetary nursery about 1600 light years away. Here lies a complex of molecular clouds where over 200 organic molecules are found. More than 150 protoplanetary disks have been found here in images taken by the Hubble Space Telescope, the upper inset showing a few such disks

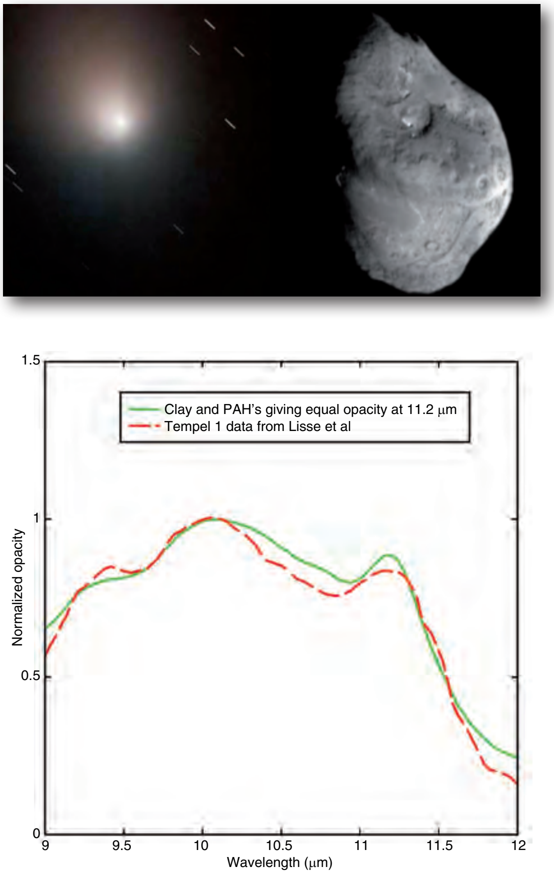

Figure 3. The Deep Impact Mission of 4 July 2005. (**a**) Hubble telescope image of Comet Tempel 1 just before impact (left) and spacecraft image of the comet on the approach of the Deep Impact probe. (**b**) A combination of clay and organics explain the observed spectrum of material ejected from Tempel 1

it would appear that only two options remain open: the origin of life on Earth was an extremely improbable event that occurred and will effectively not be reproduced elsewhere; or, a very much bigger system than was available on Earth, and a longer timescale was involved in an initial origination event, after which life was somehow transferred to Earth. In collaboration with Fred Hoyle, I have argued in favour of the latter option[15–17], while others may prefer to discard the probability argument as insecure, and assert that life must of necessity arise readily by an undiscovered process whenever and wherever the right conditions are found.

The molecular clouds in Orion are of course much bigger in scale than anything on Earth, but in the gaseous interstellar medium all that one could really hope to achieve is the production of organic molecules through gas-phase chemistry. These organic molecules must then enter a watery medium in suitably high concentrations to begin the presumptive prebiotic chemistry that may have eventually led to life. In the formation of a planetary system such as the solar system (and the proto-planetary nebulae such as are seen in Figure 2), the first solid objects to form are the comets. These icy objects would contain the molecules of the parent interstellar cloud, and for a few million years after they condensed would have liquid water interiors due to the heating effect of radioactive decays. If microbial life was already present in the parent interstellar cloud, the newly formed comets could serve to amplify it over a very short timescale.

But prior to life being generated anywhere, primordial comets would provide trillions of 'warm little ponds' replete with water, organics and nutrients, their huge numbers diminishing vastly the improbability hurdle for life to originate. Recent studies of comet Tempel 1 (Figure 3) have shown evidence of organic molecules, clay particles as well as liquid water, providing an ideal setting for the operation of the 'clay theory' of the origin of life[18,19]. Together with Janaki Wickramasinghe and Bill Napier, I have argued that a single primordial comet of this kind will be favoured over all the shallow ponds and edges of oceans on Earth by a factor 10^4, taking into account the total clay surface area for catalytic reactions as well as the timescale of persistence in each scenario. With 10^{11} comets, the factor favouring solar system comets over the totality of terrestrial 'warm little ponds' weighs in at a figure of 10^{15}, and with 10^9 sun-like stars replete with comets in the entire galaxy we tot up a factor of 10^{24} in favour of a cometary origin life

The next step in the argument is that once life got started in some comet somewhere, its spread in the cosmos becomes inevitable [16,17]. As we already noted, comets themselves provide ideal sites for amplification of surviving microbes that are incorporated into a nascent planetary system. Dormant micro-organisms released in the dust tails of comets can be propelled by the pressure of starlight to reach interstellar clouds. Transport of life of micro-organisms and spores within the frozen interiors of comets carries only a negligible risk of destruction, while transport in either naked form, within clumps of dust or within meteorites entails varying degrees of risk of inactivation by cosmic rays and UV light. It cannot be overemphasised, however, that the successful seeding of life requires only the minutest survival fraction between successive amplification sites [17]. Of the bacterial particles included in every nascent cometary cloud only one in 10^{24} needs to remain viable to ensure a positive feedback loop for panspermia. All the indications are that this is indeed a modest requirement that is hard, if not impossible, to violate.

While amplification of micro-organisms within primordial comets could supply a steady source of primitive life (Archaea and bacteria) to interstellar clouds and thence to new planetary systems, the genetic products of evolved life could also be disseminated on a galaxy-wide scale [20,21]. The most recent work on this topic was done by Janaki Wickramasinghe and Bill Napier [22,23]. Our present-day solar system, which is surrounded by an extended halo of some 100 billion comets (the Oort Cloud), moves around the centre of the galaxy with a period of 240 million years. Every 40 million years, on average, the comet cloud becomes perturbed due to the close passage of a molecular cloud. Gravitational interaction then leads to hundreds of comets from the Oort Cloud being injected into the inner planetary system, some to collide with the Earth. Such collisions can not only cause extinctions of species (as one impact surely did 65 million years ago, killing the dinosaurs), but they could also result in the expulsion of surface material back into space (see Figure 4). A fraction of the Earth-debris so expelled survives shock-heating and could be laden with viable microbial ecologies as well as genes of evolved life. Such life-bearing material could reach newly forming planetary systems in the passing molecular cloud within a few hundred million years of the ejection event. A new planetary system thus comes to be infected with terrestrial microbes terrestrial genes that can contribute, via horizontal gene transfer, to an ongoing process of local biological evolution. Once life has got started and evolved on an alien planet or planets of the new system the same process can be repeated (via comet collisions) transferring genetic material carrying local evolutionary 'experience' to other molecular clouds and other nascent planetary systems. If every life-bearing planet transfers genes in this way to more than one other planetary system (say 1.1 on the average) with a characteristic time of 40 million years then the number of seeded planets after 9 billion years (lifetime of the galaxy) is $(1.1)^{9000/40}{\sim}2\text{x}10^{9}$. Such a large number of 'infected' planets illustrates that Darwinian evolution, involving horizontal gene transfers, must operate not only on the Earth or within the confines of the solar system, but on a truly galactic scale. Life throughout the galaxy on this picture would constitute a single connected biosphere.

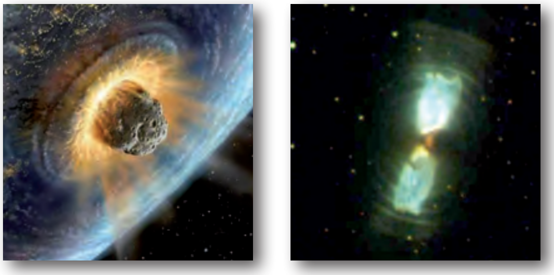

Figure 4. Impacts of comets onto the Earth, particularly occurring during close encounters of our solar system with molecular clouds such as Orion, leads to splashback of viable biomaterial that can reach nearby nascent planetary systems within 100,000 years

Much astrobiological attention is being focused now-adays on the planet Mars with attempts to find evidence of contemporary life, fossil life and potential life habitats[24]. The Jovian moon Europa, the Venusian atmosphere, the outer planets and comets are also on the astrobiologist's agenda but further down the timeline. The unambiguous discovery of life on any one of these solar system objects would be a major scientific breakthrough and would offer the first direct test of the concept of an interconnected biosphere.

The discovery of bacteria and Archaea occupying the harshest environments on Earth continues to provide indirect support for panspermia. Viable transfers of microbial life from one cosmic habitat to another requires endurance of high and low temperatures as well as exposure to low fluxes of ionizing radiation delivered over astronomical timescales, typically millions of years. The closest terrestrial analogue to this latter situation exists for micro-organisms exposed to the natural radioactivity of the Earth, an average flux of about 1 rad per year. Quite remarkably microbial survival under such conditions is well documented. Dormant micro-organisms in the guts of insects trapped in amber have been revived and cultured

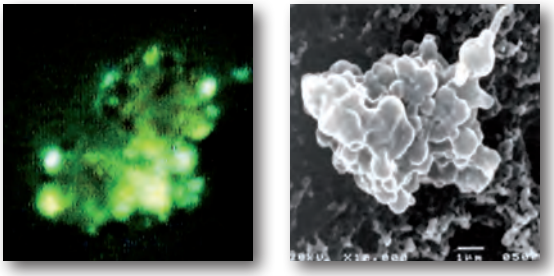

Figure 5. Stratospheric dust collected aseptically from an altitude of 41 km on 20 January 2001 showed evidence of clumps of viable, but not culturable bacteria. The left panel shows a clump fluorescing under the action of a carbocyanine dye, and the right panel shows a scanning electron microscope image consistent with a clump of cocci and a bacillus

after 25–40 million years[25], and a microbial population recovered from 8 million-year-old ices has shown evidence of surviving DNA[26]. All this goes to show that arguments used in the past to 'disprove' panspermia on the grounds of survivability during interstellar transport are likely to be seriously flawed.

In conclusion, comets are beginning to acquire a prime importance and relevance to the problem of the origin of life. It would surely be prudent to study these celestial wanders more carefully. From 1986 onwards, infrared spectra of comets have shown consistency with the presence of biologically relevant material, perhaps even intact desiccated bacteria. With some 50–100 tonnes of cometary debris entering the Earth's atmosphere on a daily basis the collection and testing of this material for signs of life should in principle at least be straightforward. Such a project was started in 2001 by the Indian Space Research Organisation in partnership with Cardiff University. Samples of stratospheric aerosols collected using balloon-borne cryosamplers were investigated independently in Cardiff, Sheffield and India, and have revealed tantalizing evidence of microbial life[28,29]. A particularly interesting component of the collected samples was in the form of 10 μm clumps that have were identified by scanning electron microscopy and fluorescence tests as being viable but not culturable micro-organisms (Figure 5). Because such large aggregates are virtually impossible to loft to 41 km, a *prima facie* case for their extraterrestrial cometary origin has been made. However, in view of the profound importance of any conclusion such as this, it is a high priority to repeat projects of this kind. Compared with other space projects for solar system exploration, the budgets involved are trivial, but the scientific pay-off could be huge. We might ultimately hope for confirmation that Darwinian evolution takes place not just within a closed biosphere on Earth, but extends over a large and connected volume of the cosmos. ■

Chandra Wickramasinghe is a distinguished astronomer who, together with the late Sir Fred Hoyle, pioneered the modern theory of cometary panspermia. His recent book 'A Journey with Fred Hoyle' published by World Scientific traces the history of this collaboration. He is a Professor at Cardiff University and Director of the Cardiff Centre for astrobiology. email: ncwick@googlemail.com

References

1. Darwin, C. (1859) On the Origin of Species by Means of Natural Selection, John Murray, London
2. Oparin, A.I. (1953) The Origin of Life (trans. S. Margulis), Dover Publications, New York
3. Haldane, J.B.S. (1929) The Origin of Life, Chatto & Windys, London
4. Urey, H.C. (1952) Proc. Nat. Acad. Sci. USA **38**(4), 351–363
5. Hoyle, F. and Wickramasinghe, N.C. (1977) Nature **270**, 323–324
6. Wickramasinghe, N.C., Wickramasinghe, J.T. and Mediavilla, E. (2004) Astrophys. Space Sci. **298**, 453–460
7. Woese, C. (1967) The Genetic Code, Harper and Row, New York
8. Gilbert, W. (1986) Nature **319**, 618
9. Wachtershauser, G. (1990) Proc. Nat. Acad. Sci. USA **87**(1), 200–204
10. Bohler, C., Nielson, P.E. and Orgel, L.E. (1995) Nature **376**, 578–581
11. Cairns-Smith, A.G. (1966) J. Theor. Biol. **10**, 53–88
12. Mojzsis, S.J., Arrhenius, G. Mckeegan, K.D. Harrison, T.M., Nutman, A.P. and Friend C.R.L. (1996) Nature, **384**, 55–59
13. Manning, C.E., Mojzsis S.J. and Harrison. T.M. (2006). Am. J. Sci. **306**, 303–366
14. Crick, F.H.C. and Orgel, L.E. (1973) Icarus **19**, 341–346
15. Hoyle, F. and Wickramasinghe, C. (1980) Evolution from Space, Dent, London
16. Hoyle, F. and Wickramasinghe, N.C. (1982) Proofs that Life is Cosmic, Mem. Inst. Fund. Studies Sri Lanka, No. 1 (www.panspermia.org/proofslifeiscosmic.pdf)
17. Hoyle, F. and Wickramasinghe, C. (1999) The Biochemist **21**(6), 11–18
18. Wickramasinghe, J.T., Wickramasinghe, N.C. and Wallis, M.K. (2008) Int. J. Astrobiol., in the press
19. Napier, W.M., Wickramasinghe, J.T and Wickramasinghe, N.C. (2007) Int. J. Astrobiol. **6**(4) 321–323
20. Wallis, M.K. and Wickramasinghe, N.C. (2004) Mon. Not. Roy. Astr. Soc. **348**, 52–61
21. Napier, W.M. (2004) Mon. Not. Roy. Astr. Soc. **348**, 46–51
22. Wickramasinghe, J.T. (2007) PhD Thesis, Cardiff University
23. Wickramasinghe, J.T. and Napier, W.M. (2008) Mon. Not. Roy. Astr. Soc. **387**, 153–157
24. Dartnell, L. (2008) The Biochemist **30**(4), 22–25
25. Cano, R.J. and Borucki, M. (1995) Science **268**, 1060–1064
26. Bidle, K. Lee, S-H., Marchant, D.R. and Falkowski, P.G. (2007) Proc. Nat. Acad. Sci. USA **104**(33), 13455–13460
27. Narlikar, J. V., Ramadurai, S., Bhargava, P. et al. (1998) Proceedings of SPIE Conference on Instruments, Methods and Missions for Astrobiology **3441**, 301–305
28. Harris, M.J., Wickramasinghe, N.C., Lloyd, D. et al. (2002) Proceedings of SPIE Conference on Instruments, Methods and Missions for Astrobiology **4495**, 192-198
29. Wainwright, M., Wickramasinghe, N.C, Narlikar, J.V. and Rajaratnam, P. (2003) FEMS Microbiol. Lett. **218**, 161–165
30. Wainwright, M., Al-Wajeeh, K. Wickramasinghe, N.C. and Narlikar, J.V. (2004) Int. J. Astrobiol. **6**(3), 227–229