PANSPERMIA 2000

1. Early History

The idea that life is a cosmic phenomenon has a history spanning many centuries and many cultures. In most ancient philosophies of the Orient – for instance in Vedhic and Buddhist writings – the cosmic nature of life is taken for granted: It is regarded as an inherent property of a Universe that is itself infinite, timeless and eternal.

Ideas of a broadly similar character were prevalent in Classical Greece, as seen for instance in the writings of Anaxarogas in the 5th Century BC. However the viewpoint that eventually held sway in the West was one that was represented in the philosophy of Aristotle (384-322BC). According to Aristotelian philosophy life was supposed to arise from non-living matter spontaneously whenever and wherever the right set of conditions arose. The concept is referred to as the theory of spontaneous generation, and in one form or another it came to be deeply entrenched in the Western world.

In its original form, with the limited techniques of observation and experimentation that were available in earlier times, the theory of spontaneous generation may indeed have seemed to possess some degree of *prima facie* validity. The sight of maggots crawling out of rotting meat and of fireflies emerging from dew may have served as impressive visual testimony to the concept of spontaneous generation. But upon closer inspection and more critical analysis the testimony disappears. With the invention of the microscope, and following the classic experiments of Louis Pasteur in the late 1850's it became amply clear that the ancient idea of spontaneous generation was simply wrong. Pasteur's work on the souring of milk (Pasteur, 1857a) and the fermentation of wine (Pasteur, 1857b) showed that microbial life had necessarily to be derived from pre-existing lifeforms of a similar kind. That this is so for non-microscopic larger lifeforms is of course obvious. After describing his classic experiments to the French Academy Pasteur confidently declared that the theory of spontaneous generation 'will never recover from this mortal blow' (Pasteur, 1860). Pasteur's experimental results were beyond dispute; but he was sadly to be proved wrong in the way he judged the scientists who came after him.

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Science based on Cartesian reductionist principles, found it exceedingly difficult to accept that mechanistic processes could account for a simple transition from non-living to living matter. After nearly half a century of sophisticated laboratory experiments scientists have not been able to disprove Pasteur's important contention that life can only be derived from pre-existing life. Although many claims to the contrary have been made from time to time they are all manifestly flawed. The Urey-Miller experiments (Urey, 1952; Miller, 1953) of the mid-1950's showed how amino acids and nucleotides might form from a mixture of inorganic gases (Oparin, 1953; Haldane, 1929), but such experiments do not come remotely near the desired goal of producing life from non-life. Nor do other more recent experiments such as those of Imai *et al.* (1999) who reported the production of hexaglycine under conditions thought to occur in terrestrial hot springs. Nor the experiments of Bernstein *et al.* (1999) who showed that ultraviolet irradiation of polyaromatic hydrocarbons in water ice leads to the production of some 'biologically relevant' molecules such as alcohols, quinones and ethers. What is relevant for the origin of life is not just the formation of the chemical building blocks, but the emergence of *highly* specific arrangements of these molecules into structures such as enzymes. It is the latter process that presents a taunting enigma to scientists of the present day. Recent studies of Mushegian and Koonin (1996) involving the sequencing of bacterial genomes have shown that a gene set coding for some 256 proteins may be regarded as a minimal set needed for cellular life. Using our earlier argument (Hoyle and Wickramasinghe, 1980) which gave a chance of random assembly of a single enzyme from its components of about one part in 10^{20} we now arrive at a probability of assembly of the minimal enzyme set of one part in 10^{5120}. The latter number can be regarded as a measure of the minimum information content of life. The simplest autonomous living cell with such a superastronomical information content is an entire cosmos apart from amino acids strung into biologically inert and irrelevant proteinoids.

The idea that the origin of life involved a progression of steps through an RNA world, with each individual step assumed to be far less improbable than the final hurdle, does little to solve the problem. A principle of biological determinism is concealed here, the implication being that the final information content of life is somehow contained in the laws of physics and is slowly unravelled in a sequence of predetermined steps. Such an assumption has no empirical basis, however, and so the idea has to be viewed with suspicion to say the least.

Pasteur's experiments in the 1850's and 1860's provided perhaps the most important experimental basis for panspermia. Indeed this was a conclusion that was reached quite early by the German physicist Hermann Von Helmholtz (1874) who wrote thus:

'It appears to me to be fully correct scientific procedure, if all our attempts fail to cause the production of organisms from non-living matter, to raise the question whether life has ever arisen, whether it is not just as old as matter itself, and whether seeds have not been carried from one planet to another and have developed everywhere where they have fallen on fertile soil . . . .'

Sir William Thomson (later Lord Kelvin) expanded on Pasteur's paradigm: 'Dead matter cannot become living without coming under the influence of matter previously alive. This seems to me as sure a teaching of science as the law of gravitation . . . '.

So if life had preceded the Earth, how had it arrived here and where had it come from? Earlier in the 19th century the German physician R.E. Richter had suggested that living cells might travel from planet to planet inside meteorites. Richter, a physician, had only a scant knowledge of dynamics. This enabled the German physicist J. Zollner in the 1870's to raise seemingly valid technical objections, and it needs hardly be said that such objections were eagerly seized upon by orthodox opinion. But Lord Kelvin's superior mastery of dynamics allowed him to see that there was nothing to Zollner's objections. In particular Kelvin noted that evaporation from the outside of a large meteorite keeps its inside cool, thereby reasserting the possibility that organisms could be carried from planet to planet inside meteorites. In his presidential address to the 1871 meeting of the British Association in Edinburgh, Lord Kelvin drew the following remarkably modern picture (Thomson, 1871), advocating what could now be recognised as the theory of planetary panspermia:

'When two great masses come into collision in space, it is certain that a large part of each is melted, but it seems also quite certain that in many cases a large quantity of debris must be shot forth in all directions, much of which may have experienced no greater violence than individual pieces of rock experience in a landslip or in blasting by gunpowder. Should the time when this earth comes into collision with another body, comparable in dimensions to itself, be when it is still clothed as at present with vegetation, many great and small fragments carrying seeds of living plants and animals would undoubtedly be scattered through space. Hence, and because we all confidently believe that there are at present, and have been from time immemorial, many worlds of life besides our own, we must regard it as probable in the highest degree that there are countless seed-bearing meteoric stones moving about through space. If at the present instant no life existed upon the earth, one such stone falling upon it might, by what we blindly call natural causes, lead to its becoming covered with vegetation.'

2. Svante Arrhenius

The next facet in the story is associated with the Swedish Chemist and Nobel laureate Svante Arrhenius (1908), whose book *Worlds in the Making* appeared in English in 1908. Arrhenius' contribution rested on two main points, one good, one not so good. The good point was that microorganisms possess unearthly properties, properties that cannot be explained by natural selection against a terrestrial environment. The example for which Arrhenius himself was responsible was the taking of seeds down to temperatures close to zero Kelvin, and of then demonstrating their viability when reheated with sufficient care. Many other ‘unworldly’ properties have come to light over the years to which we shall have occasion to refer below.

The not-so-good point was that Arrhenius conceived of microorganisms travelling individually and unprotected through the galaxy from star system to star system. He noticed that organisms with critical dimensions of 1 micron or less are related in their sizes to the typical radiation wavelengths from dwarf stars in such a way that radiation (light) pressure can have the effect of dispersing these particles throughout the galaxy. But space-travelling individual bacteria would be susceptible to deactivation and damage from the ultraviolet light of stars, and this was already known in the first decades of the century.

P. Becquerel (1924) mounted an attack on Arrhenius’ views in 1924, on the basis of possible ultraviolet damage and this attack was widely accepted and repeated many times since. But several other facts of relevance to this problem were not known at the time.

3. Extreme Hardihood of Bacteria

On the whole microbiological research of the past 10 years has shown that bacteria and other microorganisms are remarkably space-hardy, far more than Arrhenius may have ever imagined. Microorganisms known as thermophiles and hyperthermophiles are present at temperatures above boiling point in oceanic thermal vents. Entire ecologies of microorganisms are present in the frozen wastes of the Antarctic ices. A formidable total mass of microbes exists in the depths of the Earth’s crust, some 8 kilometres below the surface, greater than the biomass at the surface (Gold, 1992). A species of phototropic sulfur bacterium has been recently recovered from the Black Sea that can perform photosynthesis at exceedingly low light levels, approaching near total darkness (Overmann *et al.*, 1992). There are bacteria (e.g. *Deinococcus radiodurans*) that thrive the cores of nuclear reactors. Such bacteria perform the amazing feat of using an enzyme system to repair DNA damage, in cases where it is estimated that the DNA experienced as many as a million breaks in its helical structure.

There is scarcely any set of conditions prevailing on Earth, no matter how extreme that is incapable of harbouring some type of microbial life. As for ultraviolet damage under space conditions, this is very easily shielded against. A carbonaceous coating of only a few microns thick provides essentially a total shielding against ultraviolet light, and there are several modern experiments that have demonstrated precisely that (Secker *et al.*, 1994). Next, let’s note that many types of microorganisms are not really killed by ultraviolet light, they are only deactivated. And this happens through a shifting of certain chemical bonds contained in the genetic structures of the organisms, without destroying the genetic structures themselves. And this permits the original properties to be recovered once the ultraviolet radiation has been shut off. There is also a recent finding that some bacteria are astonishingly resistant to ultraviolet light, a phenomenon not known or suspected in 1924 at the time of P. Becquerel (1924). Furthermore, we know that microorganisms that are normally sensitive to ultraviolet light can, through repeated exposures, be made just as insensitive as the more resistant kinds – yet another unearthly property. These are all properties which Arrhenius did not know about and which obviously support his position very strongly.

4. Interstellar Organic Molecules

Notwithstanding the remarks of the previous section bacteria which have no protective coatings and which are exposed remorselessly to cosmic rays and to the background of starlight in open regions of interstellar space, in the so-called diffuse clouds, would be subject to degradation and eventual destruction. Microorganisms expelled from any galactic source into unshielded regions of interstellar space will firstly become deactivated. Then the deactivated particles will be subject to steadily increasing degradation, ending in a production of free organic molecules and polymers, similar to what astronomers have been discovering since the late 1960's. Today an impressive array of such molecules has been detected and among the list are a host of hydrocarbons, polyaromatic hydrocarbons, the amino acid glycine and vinegar. Such organic molecules that pervade the interstellar clouds make up a considerable fraction of the available galactic carbon. Theories of how interstellar organic molecules might form via non-biological processes are still in their infancy, and in terms of explaining the facts leave much to be desired.

The overwhelming bulk of organic matter on the Earth is indisputably derived from biology, much of it being degradation products of biology. Might not the same processes operate in the case of interstellar organic molecules? The polyaromatic hydrocarbons that are so abundant in the cosmos could have a similar origin to the organic pollutants that choke us in our cities – products of degradation of biology, biologically generated fossil fuels in the urban case, cosmic microbiology in the interstellar clouds. The theory of cosmic panspermia that we propose leads us to argue that interstellar space could be a graveyard of cosmic life as well as its cradle. Only the minutest fraction (less than one part in a trillion) of the interstellar bacteria needs to retain viability, in dense shielded cloudlets for instance, for panspermia to hold sway. Commonsense dictates that this is unavoidable.

5. Interstellar Dust: Inorganic Models

Our own personal rendezvous with panspermia began with our attempts to understand the nature of cosmic dust. We embarked on this work in the 1960's, and from then on the scope of a project that started as a simple astronomical investigation expanded to proportions that could not have been imagined. Cosmic dust grains populate the vast open spaces between stars of the Milky Way, showing up as a cosmic fog, dense enough in many directions to blot out the light of distant stars. Remarkably these grains appear to be much the same in their physical and chemical characteristics in whichever direction we look outwards from the Earth. They are of a size that would be typical for a bacterium, a micrometre or less.

A fact that impressed us from the outset was that the total mass of interstellar dust in the galaxy is as large as it possibly can be if all (or nearly all) the available carbon, nitrogen and oxygen in interstellar space is condensed in the grains. The amount is about three times too large for the grains to be mainly made up of the next commonest elements, magnesium and silicon, although magnesium and silicon could of course be a component of the particles, as would hydrogen, and also many less common elements in comparatively trace quantities.

If one now asks the question: what precisely are the dust grains made of, a number of inorganic molecules composed of C,N,O in combination with hydrogen present themselves as possible candidates. These include water ice, carbon dioxide, methane, ammonia, all these materials being easily condensable into solids at temperatures typically of about 20–50 degrees Kelvin, which is the average temperature of the grains. During the decade starting from the early 1960's we studied the properties of a wide range of inorganic grain models, comparing their electromagnetic properties against the formidable number of observations that were beginning to emerge. Such models stubbornly refused to fit the available data to anything like the precision that was required. The correspondences between predictions for assemblies of inorganic particles and the observations could be lifted to a certain moderate level of precision but never beyond that, no matter how hard one tried.

6. Organic Dust

It was a milestone in our progress towards interstellar panspermia when one of us (NCW) realised that there is another very different class of materials that can be made from the same four commonest elements – C,N,O,H, namely organic materials, possibly of a polymeric type (Wickramasinghe, 1974). Of course there are a vast number of organic compositions that are possible, making for a great number of further investigations that could be made. With our experience of the prevalence of biogenic terrestrial organics, it is fair to say that we had our eyes on a possible biological origin from the outset. By the mid-1970's, the astronomical observations were spanning a large range in wavelength, from 30 microns in the infrared, through the near infrared, into the visible spectrum, and further into the ultraviolet. So a satisfactory theory of the nature of grains had by now to satisfy a very large number of observational constraints.

In 1979 we stumbled on a result that led to many further discoveries, all pointing firmly in the direction of panspermia. When we examined the light scattering properties of freeze-dried bacterial particles (hollow organic grains) of the type one might expect to occur in space, a remarkable degree of correspondence with astronomical data emerged. Such a precise correspondence was not found possible for any inorganic, non-biological grain model.

Another piece of evidence that we had uncovered at about the same time was that a broad absorption feature in interstellar dust centred on the wavelength 2175A (which we originally attributed to graphite) matched a large class of aromatic molecules, quinoline and quinozoline being the first examples we discussed.

Perhaps the most startling confirmation of the bacterial model followed the pioneering observations by D.T. Wickramasinghe and D.A. Allen (1981) of a source of infrared radiation, GC-IRS7, located near the centre of our galaxy. The spectrum of this source revealed a highly detailed absorption profile extending over the 2.9–3.8 micrometre wavelength region, indicative of combined CH, OH and NH stretching modes. A laboratory spectrum of the desiccated bacterium *E. Coli*, obtained some months *earlier* by S. Al-Mufti, together with a simple modeling procedure provided an exceedingly close point by point match to the astronomical data over the entire 2–4 micron waveband. At this stage we found there was no alternative but to face up squarely to the conclusion that a large fraction of the interstellar dust were not merely hollow and organic, but they *must* spectroscopically be indistinguishable from freeze-dried bacterial material. In our galaxy alone the total mass of this bacterial-type material had to be truly enormous, weighing a formidable 10^{33} tonnes.

7. Replication Properties of Bacteria

By far the simplest way to produce such a vast quantity of small organic particles everywhere of the sizes of bacteria is from a bacterial template. The power of bacterial replication is immense. Given appropriate conditions for replication, a typical doubling time for bacteria would be two to three hours. With a continuing supply of nutrients, a single initial bacterium would generate some 2^{40} offspring in 4 days, yielding a culture with the size of a cube of sugar. Continuing for a further 4 days and the culture, now containing 2^{80} bacteria would have the size of a village pond. Another 4 days and the resulting 2^{120} would have the scale of the Pacific Ocean. Yet another 4 days and the 2^{160} bacteria would be comparable in mass to a molecular cloud like the Orion Nebula. And 4 days more still for a total since the beginning of 20 days, and the bacterial mass would be that of a million galaxies. No abiotic process remotely matches this replication power of a biological template. Once the immense quantity of organic material in the interstellar material is appreciated, a biological origin for it becomes an almost inevitable conclusion.

8. Cometary Panspermia

The sources of biological particles in interstellar clouds are comets according to the theory developed in this book. An individual comet is a rather insubstantial object. But our solar system possesses so many of them, perhaps more than a hundred billion of them, that in total mass they equal the combined masses of the outer planets Uranus and Neptune, about 10^{29} grams. If all the dwarf stars in our galaxy are similarly endowed with comets, then the total mass of all the comets in our galaxy, with its 10^{11} dwarf stars, turns out to be some 10^{40} grams, which is just the amount of all the interstellar organic particles.

How would microorganisms be generated within comets, and then how could they get out of comets? We know as a matter of fact that comets do eject organic particles, typically at a rate of a million or more tons a day. This was what Comet Halley was observed to do on March 30–31, 1986. And Comet Halley went on doing just that, expelling organic particles in great bursts, for almost as long as it remained within observational range. The particles that were ejected in March 1986 were well placed to be observed in some detail. No direct tests for a biological connection had been planned, but infrared observations pointed unexpectedly in this direction. As shown in this book the infrared emission spectrum of dust from Comet Haley obtained by D.T. Wickramasinghe and D.A. Allen matched precisely the laboratory spectrum of bacterial grains. An independent analysis of dust impacting on mass spectrometers aboard the spacecraft Giotto also led to a complex organic composition that was fully consistent with the biological hypothesis. Broadly similar conclusions have been shown to be valid for other comets as well, in particular Comet Hyakutake and Comet Hale-Bopp. Thus one could conclude from the astronomical data that cometary particles, just like the interstellar particles, are *spectroscopically* identical to bacteria.

In summary, the logical scheme for the operation of cometary panspermia is as follows: The dust in interstellar clouds must always contain the minutest fraction of bacteria (less than a trillionth) that retain viability despite the harsh radiation environment of space. This exceedingly modest requirement of survival would be utterly impossible to violate, so panspermia becomes inevitable. When a new star system (eg. a solar system) forms from interstellar matter, comets condense in the cooler outer periphery as a prelude to planet formation. Each such comet incorporates at the very least a few billion bacteria, and these bacteria are quickly reactivated and begin to replicate in the warm interior regions of the comets, thus producing vast numbers of progeny. As a fully fledged stellar or planetary system develops, comets that plunge into the inner regions of the system release vast quantities of bacteria in the manner discussed earlier for our own solar system. Some of the evaporated bacterial material is returned into the interstellar medium. New stars and star systems form and whole cycle continues with a positive feedback of biologically processed material.

9. Microfossils in Meteorites

In the mid-1960's H. Urey, and later G. Claus, B. Nagy and D.L. Europa (Claus *et al.*, 1963) examined the Orgueil carbonaceous meteorite which fell in France in 1864, microscopically as well as spectroscopically. They claimed to find evidence of organic structures that were similar to fossilised microorganisms, algae in particular. The evidence included electron micrograph studies, which showed substructure within these so-called 'cells'. Some of the structures resembled cell walls, cell nuclei, flagella-like structures, as well as constrictions in some elongated objects to suggest a process of cell division. If these 'organised elements' were indeed microbial fossils the question arises as to how such structures were included within carbonaceous meteorites. This question could not be satisfactorily answered in 1960, although with the wisdom of hindsight we could now say the answer was obvious: carbonaceous chondrites, typified by Orgueil, represent the residue of comets that once contained microbial life thriving within subsurface pools. Carbonaceous chondrites can thus be thought of as fragments of biological comets that have been progressively stripped of volatiles, and within which sedimentation and compaction of microorganisms may have occurred over hundreds of perihelion transits. Unfortunately a hostile establishment that was determined to stop a seemingly inevitable trend towards panspermia quickly seized upon these early claims of meteoritic microfossils. The tactic employed was to point to a very small number of alleged microfossils that were most likely to be terrestrial contaminants. This still left an overwhelming number of organic structures for which no satisfactory explanation could be offered.

In the early 1980's the German paleontologist H.D. Pflug (1984) reopened the issue of microbial fossils in carbonaceous meteorites. Pflug used techniques that were distinctly superior to those of Claus and his colleagues and found a profusion of organised elements comprised of organic matter in thin sections prepared from a sample of the Murchison meteorite. The method adopted by Pflug was to dissolve-out the bulk of the minerals present in a thin section of the meteorite using hydrofluoric acid, doing so in a way that permits the insoluble carbonaceous residue to settle with its original structures in tact. It was then possible to examine the residue in an electron microscope without disturbing the system from outside. The patterns that emerged were stunningly similar to certain types of terrestrial microorganisms. Scores of different morphologies turned up within the residues, many resembling known microbial species. It would seem that contamination could now be excluded by virtue of the techniques used. No convincing non-biological alternative to explain all the features were offered by critics, although the statement that they were all 'mineralogical artifacts' that somehow trapped organics from a surrounding medium came to be widely publicised. Despite these criticisms a renewed attempt to explore the question of microfossils in carbonaceous meteorites has been undertaken in 1997 by R.B. Hoover of the NASA Marshal Space Flight

Centre. This new work appears to corroborate Pflug's findings of microfossils in the deep interiors of carbonaceous chondrites (Hoover, 1997).

Clumps of interplanetary dust particles of cometary origin have been collected in the stratosphere over many years using sticky paper flown aboard U2 aircraft. These so-called Brownlee particles have consistently shown evidence of carbonaceous material, some of which might be exceedingly complex. By comparing one such carbonaceous structure discovered by Bradley *et al.* (1984) with a microbial fossil found in the Gunflint cherts of N. Minnesota we noted already in 1985 (Hoyle *et al.*, 1984) that a biological explanation (a partially degraded iron-oxidising bacterium) is the most plausible. Further studies by S.J. Clemett *et al.* (1993) of eight Brownlee particles, which were identified as cometary dust, revealed the presence of exceedingly complex organic molecules including aromatic and aliphatic hydrocarbons. This discovery represented yet another step towards identifying cometary particles as being biogenic.

10. The Mars Meteorite ALH 84001

The latest chapter in the exploration of panspermia was opened in August 1996 with studies of a 1.9 kg meteorite (ALH 84001) which is believed to have originated from Mars (McKay *et al.*, 1996). ALH84001 is just one of a group of meteorites discovered in 1984 in Allan Hills, Antarctica, which is thought to have been blasted off the Martian surface due to an asteroid or comet impact some 15 million years ago. This ejecta orbited the sun until 13 000 years ago when it plunged into the Antarctic and remained buried in ice until it was discovered. The presumed Martian origin of these meteorites (also known as SNC meteorites) seems to have been confirmed by several independent criteria. One that is perhaps amongst the most cogent involves the extraction of gases trapped within the solid matrix which were found to resemble in relative abundances the gases that were discovered in the Martian atmosphere. Also the ratio of oxygen isotopes $^{17}O/^{18}O$ in the mineral component matches the value found on Mars so closely that there is no reason to doubt a Martian origin.

A team of NASA investigators led by David S. McKay (1996) have found that within the meteorite ALH 84001 there are sub-micron sized carbonate globules around which complex organic molecules are deposited. As we have already noted these molecules, including polyaromatic hydrocarbons, are characteristic products of the degradation of bacteria. The most striking evidence showed up as strings of elongated structures that were similar to terrestrially occurring microfossils of nanobacteria. Associated with these structures there were elongated crystals of magnetite (iron oxide) very similar to structures found in certain types of magnetic bacteria. Such elongated crystal structures do not form through any known non-biological process.

McKay and his colleagues admit that their proposed identification involves a process of multi-factorial assessment. The totality of the available evidence, in their view, points to a microbial origin, although each single piece of evidence may be capable of a more conservative interpretation. Many such interpretations have since been offered and consensus opinion seems to be veering cautiously towards rejecting rather than accepting the original NASA claims. The jury is still out and arguments rage concerning many issues, for instance the temperature at which the carbonate globules condensed, and whether the putative biological structures could survive these temperatures. McKay and his colleagues still vigorously defend their original contention and are advancing even stronger arguments in its support. The debate seems destined to continue, however, perhaps until the day when Martian samples are returned to Earth.

If the explanation of McKay et al is eventually upheld, the deposition of the microfossils coincident with the condensation of carbonate globules can be dated at 3.6Ga BP. So one might conclude that microbial life existed on Mars some 3600 million years ago, probably concurrently with the earliest evidence of microbial fossils on the Earth. In accordance with the theory of cometary panspermia it would appear likely that both the Earth and Mars came to be seeded with bacterial life almost at the same time.

11. Planetary Panspermia

An alternative version of panspermia that is becoming increasingly popular is known by the term *planetary panspermia*, and follows perhaps unwittingly in the tradition of Lord Kelvin. The trend is based on a growing body of evidence that planetary material could be exchanged between the inner planets of the solar system. There are meteorites recovered on Earth that originated on the Moon (lunar meteorites) and others, as we have seen, the SNC meteorites that originated on the Mars. We also know from studies of lunar craters that both the Earth and the Moon were subject to intense cometary and asteroid bombardment prior to 4Gy ago. And the same process would have continued at a much-reduced intensity at later epochs.

In a typical impact of a 10 km sized comet with a planet such as Mars (which occurs on the average every few tens of Ma at the present time) most of the material of the impactor and crater will be vaporised. However, material at the periphery of an impact crater will be ejected in the form of rocks and boulders that would be subject only to mild shocking. Such rocks could harbour viable microbes and microbial spores in their interiors and be ejected in many directions over a wide range of velocities. A fraction of boulders that have velocities in excess of the planetary escape speed (5 km s^{-1} for Mars, 11.2 km s^{-1} for Earth) would be spread over a large volume of interplanetary space, and thus be available to impact other planetary bodies. Microbes within boulders that survived the trauma of the initial comet impact and subsequent travel outwards through the atmosphere of the parent planet face a further hazard on re-entering the atmosphere of a receiving planet. But these hazards will be overcome for boulders of the size of a metre or more: only the outer layers become ablated, the interior remaining cool. Since there is now no doubt that ALH84001 was a fragment of rock blasted off the Martian surface, and since fragile chemical stuctures were found to survive the transit to Earth, the survival of microbes or spores in the interiors of similar interplanetary missiles is no longer in doubt.

These considerations have led to speculations that life could have started first on Mars and then been transferred to Earth via an ALH84001 type missile some 3600 million years ago. This in our view begs the question of how life got started on Mars. Although the transference of life between planets is possible, cometary panspermia would seem to be the stronger process for transferring life within the solar system.

12. Evidence from Geology

Along with the accumulation of astronomical evidence supporting panspermia in one form or another there has been evidence from geology as well. The earliest evidence for terrestrial life has now been pushed back beyond 3.83 billion years BP, well into an epoch when we know for certain that the Earth was being severely pummeled by comet and meteorite impacts (Mojzsis *et al.*, 1996). This evidence comes in the form of a slight depletion of the lighter isotope of carbon ^{12}C relative to ^{13}C in the oldest metamorphic rocks. The argument is that life has a slight preference for the lighter isotope of carbon and this is reflected in the carbon extracted from rocks that could date back to about 4 billion years. Whilst the early epoch of heavy bombardment would not have been conducive to prebiotic chemistry, it would nevertheless have offered ample scope and many occasions for the transfer of cometary life to Earth. It is interesting to note that this mechanism for transfering life from comets to Earth would permit some types of microbial life adapted to high pressures and subsurface conditions to become trapped in a stable way. As the impacts of comets and asteroids continued to add material to the Earth's crust in the last stages of the 'late accretion epoch' a deep hot biosphere (Gold, 1992), such as we now have, would easily have been generated.

13. More Evidence from Microbiology

We have discussed earlier how modern microbiology is yielding a wealth of new discoveries that support the theory of panspermia. Discoveries of extremophiles, bacteria that can withstand the harshest of conditions, for instance, are inconsistent with an Earth-centred view of life. Furthermore, from recent explorations of the solar system we know that other planetary bodies besides Earth might have conditions appropriate to serve as habitats for microbial life. For instance, the Jovian satellite Europa with evidence of subsurface oceans provides many opportunities for a highly developed microbiota. Likewise there could be scope for extanct life on Mars, perhaps in secluded subsurface niches. The presence of a deep hot biosphere on Earth at depths of 8 km, to which we have already alluded, lends credibility to yet another option: that of life existing in vast quantity in the deep interiors of planetary bodies.

According to our version of panspermia life on Earth began with the introduction of microorganisms from comets. But this process could not have stopped at some distant time in the past for the simple reason that comets have been with us throughout. In our view the evolution of terrestrial life is controlled and directed by the continuing input of cometary debris in the form of bacteria, fragments of bacteria and smaller particles such as viruses and viroids. It is well known that viral genes sometimes come to be included in the genomes of multi-cellular lifeforms, and that such genes could serve as potential for further evolution. Without this input of cometary genes life on Earth could not have evolved beyond the stage of a simple ancestral microbe.

Over the past few years it has been discovered that there are vastly more bacterial species at every location on the Earth than has hitherto been thought. A mere 10 000 bacterial species had been identified ten years ago; now this number is estimated as many millions, even billions (Margulis and Schwartz, 1988). The existence of this truly vast number of bacterial species has been inferred indirectly from DNA studies, and most have not even yet been cultured, and perhaps never will. It appears that many of these microbial species are in fact ‘extremophiles’, bacteria that appear to seek extreme and hitherto uncharted environments (Postgate, 1994). They are present in the soil and in surface water, evidently doing nothing – waiting for the right host, right conditions – perhaps they are falling from the skies.

14. Some Biochemical Evidence

One of the great advances of biology in the past decade has been the development of techniques for mapping the precise sequences of bases in RNA or DNA in genes. Using such maps, particularly maps of bacterial RNA, it is in principle possible to construct phylogenetic trees in much the same way that linguists reconstruct lineages of ancient language from living counterparts. From this procedure it was thought that three major kingdoms of life, the bacteria, the archaea and the eukarya can be distinguished, all of which might be descended from a common ancestor over 3.85 billion years ago. New data on genome sequences are casting serious doubts, not only on the division into 3-kingdoms, but also on the very concept of a common terrestrial anscestor (Pennisi, 1998; Woese, 1998; Poole *et al.*, 1998; Wray *et al.*, 1996). When different genes are used for constructing evolutionary trees, several equally likely connections seem to emerge. The genes of archaea, bacteria and eukarya display considerable intermixing between possible evolutionary branches calling into question the evolutionary schemes that have been proposed. A bacterium called *Aquifex aeolicus* that lives in hot springs at temperatures close to boiling point was thought until recently to have a decisively greater antiquity than other terrestrial archaea. But this conclusion has come to be questioned after a complete genetic map of the bacterium became available. *Aquifex* contains only one gene that is not found in normal bacteria, implying that a switch between heat-loving and normal bacterial types might be a more trivial transition than was hitherto thought. From a wide range of normally occurring (incident) bacterial types, *Aquifex* just happened to be the best suited to the boiling water habitat in which it is found.

There are several recent reports of genes that appear to be older, when dated by the rate of sequence variation, than the composite systems or species, in whose genomes they are included (Kumar and Blair-Hedges, 1998; Cooper and Penny, 1997). Other reports show that genes required by more highly evolved species may reside without evident function in the genomes of prokaryotes (Bult *et al.*, 1996) or viruses (Smith *et al.*, 1998). One cannot help but notice that these findings corroborate the concept of cosmic bacteria and cosmic genes that we have advocated for over two decades and discussed at length in this book.

15. Unequivocal Proof

A direct way to test cometary panspermia would be to examine a sample of cometary material under the microscope and search for signs of microbial life. Comets are literally at our doorstep and the technology to carry out the relevant microbiological experiments has been available for at least a decade. The basic procedure would involve collection of cometary material as it enters the stratosphere, with suitable precautions being taken to eliminate spurious contamination from terrestrial sources, and then to examine the samples for extraterrestrial microorganisms. With a daily input of cometary debris averaging some 500 tonnes, the possibility of detecting infalling microbes must surely exist.

Historically the earliest experiments to search the upper atmosphere for microorganisms were carried out using high altitude balloons in the early to mid-1960's. Although microbiological techniques available at the time were rather primitive compared to the present, there were already some intriguing indications of the presence of extraterrestrial microbes in air samples collected at heights of 30 km and above (Bruch, 1967). Positive detection of microorganisms at 39 km and a population density that increased with height pointed to a possible extraterrestrial source. Not surprisingly these early results were not taken seriously, nor were they followed up at a later date with more refined experiments as the available microbiological techniques evolved.

Despite the publicly declared objectives of NASA which include the search for life outside the Earth, the reigning scientific paradigm of Earth-centred life was so powerful that even the slightest hint of a contradiction tended to be brushed aside. This philosophy of 'bully conquers all' showed no signs of slackening even though evidence for panspermia continued to grow in strength through the 1980's and 1990's.

In August 1996 the reports by a NASA group of the possible detection of micro-fossils in a Martian meteorite (ALH84001) provided a watershed for panspermia. Investigations of panspermia were immediately elevated to the status of legitimate scientific inquiry. Many international scientific establishments that had turned their backs to panspermia and exobiology were announcing intentions to step up support for research in these areas. Almost overnight it would appear that wheels started to turn and a paradigm shift was in sight. As a sign of change we note that Mars sample return missions in the coming decade have incorporated plans for the strictest microbiological quarantine procedures to guard against the possibility of bringing back dangerous Martian microbes to the Earth.

The sample return cometary mission 'Stardust', which was launched on 7 February 1999 heading to Comet Wildt-2 (rendezvous date, 2 January 2004) was conceived and planned before a change of attitude to panspermia took place. In the event no microbiological experiments as such were catered for. The comet dust is to be captured in a 'particle catcher' filled with aerogel, a material of extremely low density. The hope is that the aerogel would act as a soft landing cushion to slow down particles from an initial relative speed of 6.1 km s^{-1} to rest fairly gently, without significantly modifying original chemical structures. The thinking behind the experiment was to bring back prebiotic organic molecules. No provisions were made for the circumstance that living cells might be present, so the best one might hope for when we get samples back in 2006 is the intervention of serendipity. Perhaps one might find evidence of 'dead bacteria' or other clues for life in the molecules that are recovered.

Long ahead of the year 2006 stratospheric balloon experiments are being planned by the Indian Space Research Organisation (ISRO) in collaboration with the group in Cardiff (Narlikar *et al.*, 1998). These long overdue experiments may well yield the first decisive evidence of panspermia at a minute fraction of the cost of space missions. State of the art microbiological procedures are to be used, along with contaminant proof cryo-pumps to collect air at various heights and to study these in various ways in the laboratory. The hope is that we might identify an ongoing input of cometary microbes to Earth.

16. Cosmological Implications

Panspermia theories we have discussed in earlier sections and throughout this book do not address the question of the ultimate origin of life, but only its transference once it has originated. In view of the superastronomical information content that is present in even the simplest living cell, attempts to produce life from non-life might be eternally doomed, not merely in the chemist's laboratory or on the primitive Earth, but *anywhere* within the framework of a finite Big-Bang type universe (Hoyle and Wickramasinghe, 1997). However, the set of astronomical data that is currently cited as support for the Standard Big-Bang Universe fits just as well another class of cosmological model (Quasi Steady State Models) that has an infinite age. One would be free within such a model to suppose that life is infinitely old, that it has always existed. Or that it is regenerated over timescales and volumes of space that are 'superastronomical'.

References

Allen, D.A. and Wickramasinghe, D.T.: 1981, *Nature* **294**, 239.

Arrhenius, S.: 1908, *Worlds in the Making*, Harper, Lond.

Becquerel, P.: 1924, *Bull. Soc. Astron.* **38**, 393.

Bernstein, M.P., Sandford, S.A., Allamandola, L.J., Gilette, J.S., Clemett, S.J. and Zare, R.N.: 1999, *Science* **283**, 1135–1138.

Bradley, J.P., Brownlee, D.E. and Fraundorf, P.: 1984, *Science* **223**, 56.

Bruch, C.W.: 1967, in: P.H. Gregory and J.L. Monteith (eds.), *Airborne Microbes Symposium of the Society of Microbiology*, p. 345, Cambridge University Press.

Bult, C.J., *et al.*: 1996, *Science* **273**, 1058.

Claus, G., Nagy, B. and Europa, D.L.: 1963, *Ann. NY Acad. Sci.* **108**, 580.

Clemett, S.J., *et al.*: 1993, *Science* **263**, 721.

Cooper, A. and Penny, D.: 1997, *Science* **275**, 1109.

Gold, T.: 1992, *Proc. Natl. Acad. Sci.* **89**, 6045–6049.

Haldane, J.B.S.: 1929, *The Origin of Life*, Chatto and Windys.

Hoover, R.B.: 1997, *Proc. SPIE Conference on Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms* **3111**, 115–136.

Hoyle, F. and Wickramasinghe, N.C.: 1980, *Evolution from Space*, J.M. Dent & Sons Lond.

Hoyle, F. and Wickramasinghe, N.C. and Pflug, H.D.: 1984, *Astrophys. Space Sci.* **113**, 20.

Hoyle, F. and Wickramasinghe, N.C.: 1990, *The Theory of Cosmic Grains*, Kluwer.

Hoyle, F. and Wickramasinghe, N.C.: 1996, *Astrophys. Space Sci.* **235**, 343.

Hoyle, F. and Wickramasinghe, N.C.: 1997, *Life on Mars: The Case for a Cosmic Heritage*, Clinical Press, Bristol.

Imai, E., Honda, H., Hatori, K., Brack, A. and Matsuno, K.: 1999, *Science* **283**, 831–833.

Johnson, F.M.: 1972, *Ann. NY Acad. Sci.* **187**, 186.

Kumar, S. and Blair Hedges, S.: 1998, *Nature* **392**, 917.

Levin, G.V. and Straat, P.A.: 1981, *J. Theor. Biol.* **91**, 41; 1981, *Icarus* **45**, 494; Digregorio, B.E., Levin, V.V. and Straat, P.A.: 1997, *Mars: The Living Planet*, Frog Ltd., Berkley Calif.

Margulis, L. and Schwartz, K.V.: 1998, *Five Kingdoms: An Illustrated Guide to the Phyla of Life on Earth*, W.H. Freeman & Co., Second Edition.

McKay, D.S., *et al.*: 1996, *Science* **273**, 924.

Miller, S.L.: 1953, *Science* **117**, 528.

Miller, S.L. and Urey, H.C.: 1959, *Science* **130**, 245.

Mojzsis, S.J., *et al.*: 1996, *Nature* **384**, 55.

Mushegian, A.R. and Koonin, E.V.: 1966, *Proc. Natl. Acad. Sci. USA* **96**, 10268–10273.

Narlikar, J.V., Ramadurai, S., Bhargava, P., Damle, S.V., Wickramasinghe, N.C., Lloyd, D., Hoyle, F. and Wallis, D.H.: 1998, *Proc. SPIE Conference on Instruments, Methods, and Missions for Astrobiology* **3441**, 301–305.

Oparin, A.I.: 1953, *The Origin of Life*, translated by S. Margulis, Dover.
Overmann, J., Cypionka, H. and Pfennig, N.: 1992, *Limnol. Oceanogr.* **37** (1), 150–155.
Pasteur, L.: 1857a, *C. R. Acad. Sci.* **45**, 913–916.
Pasteur, L.: 1857b, *C. R. Acad. Sci.* **45**, 1032–1036.
Pasteur, L.: 1860, *C. R. Acad. Sci.* **50**, 303–307.
Pennisi, E.: 1998, *Science* **280**, 672.
Pflug, H.D.: 1984, in: C. Wickramasinghe (ed.), *Fundamental Studies and the Future of Science*, Univ. College Cardiff Press.
Poole, A.M., Jeffares, D.C. and Penny, D.: 1998, *J. Mol. Evol.* **46**, 1.
Postgate, J.: 1994, *The Outer Reaches of Life*, Cambridge University Press.
Secker, J., Wesson, P.S. and Lepock, J.R.: 1994, *Astrophys. Space Sci.* **329**, 1.
Smith, M.C., *et al.*: 1998, *Science* **279**, 1834.
Thomson, W.: 1871, *British Association for the Advancement of Science*, Presidential Address at 1871 Edinburgh meeting, p. 26.
Urey, H.C.: 1952, *The Planets*, Chapter 4, Yale Univ. Press.
von Helmholtz, H.: 1874, in: W. Thomson and P.G. Tait (eds.), *Handbuch de Theortetische Physik* **1**, Pt. 2, Brancscheig.
Wickramasinghe, N.C.: 1974, *Nature* **252**, 462.
Wickramasinghe, N.C.: 1993, in: A. Mampaso *et al.* (eds.), *Infrared Astronomy*, p. 303, Cambridge University Press.
Woese, C.: 1998, *Proc. Natl. Acad. Sci.* **95**, 6854.
Wray, G.A., Levinton, J.S. and Shapiro, L.H.: 1996, *Science* **274**, 568.