Invited Paper

Panspermia in perspective

N.C. Wickramasinghe[a], F. Hoyle[a] and Brig Klyce[b]

[a]School of Mathematics, Cardiff University, PO Box 926, Senghennydd Road, Cardiff CF2 4YH, UK

[b]Acorn Enterprises LLC, 1503 Union Avenue #216B, Memphis, TN 38104-3757, USA

ABSTRACT

Panspermia, an ancient theory, was revived in its modern form by two of the present authors (H-W) in a series of publications over the period 1977 to the present day. Unpopular at first, it is now slowly gaining popularity and is coming to be discussed, albeit with a measure of apprehension, as a serious scientific possibility. A brief resume will be given of the modern scientific case for panspermia, indicating that astronomical, geological and biological evidence is moving slowly in the direction of a paradigm shift.

Keywords: Panspermia, comets, meteorites, microfossils, interstellar matter, origins of life

1. INTRODUCTION

The idea that life is cosmic, rather than purely terrestrial has itself had a long history. In most ancient philosophies of the Orient, in India for example, it seemed natural to contemplate a Universe that was timeless and eternal, and consequently, life also that was eternal as well as cosmic. The concept of cosmic life made a few brief appearances in Western philosophy. The earliest ideas that could be linked to panspermia came with the Greek Philospher Anaxoragas in the 5^{th} century BC. Next followed Aristarchus of Samos in the 3rd century BC, and then Lucretius of Rome in the 1st century BC; but thereafter these ideas lay dormant until the latter part of the nineteenth century. Over the past few years panspermia has not only staged a significant comeback but is also emerging as a major contender amongst scientific theories for the origin of life.

An idea that dominated Western thought for centuries is contained in what is known as the doctrine of spontaneous generation. According to this doctrine life is supposed to arise from inorganic matter spontaneously under suitable conditions without the intervention of any external agency. The Greek philosopher Aristotle who lived from 384-322BC stated that fireflies emerge from a mixture of warm earth and morning dew; and there were many variants of this general theme.

A modern version of the theory of spontaneous generation was introduced in the early part of this century by Oparin and Haldane[1]. The first step involves the formation of prebiological molecules, the chemical building blocks of life. It was suggested that such molecules formed in the Earth's primitive atmosphere through the action of electric discharges, such as would occur in lightning and from exposure to ultraviolet light from the sun. The organic molecules then rain down into the oceans generating an exceedingly dilute 'organic soup'. An undefined sequence of chemical transformations is next supposed to take place leading to the emergence of a primitive living system from which all other lifeforms subsequently evolve. This account of our origins occupies the first chapter of every biological textbook that has been written since the 1950's.

Attempts to justify such a scheme of events have concentrated mainly on the problem of getting the organic building blocks of living systems from inorganic molecules under laboratory conditions. The passage of high voltage electric sparks through a mixture of inorganic gases such as water, methane and ammonia can be shown to produce traces of organic chemicals including sugars, nucleotides and amino acids. This was done, for instance, in the classic experiments of Harold Urey and Stanley Miller[2,3,4] in the early 50's. A basic requirement for such experiments is that the starting mixture of gases has an overall reducing property, that is to say, an effective excess of available hydrogen over oxygen. Recently these ideas have suffered a major setback because geochemists have discovered that the Earth's primordial atmosphere was of an *oxidising* rather than of a *reducing* nature[5,6]. In such an atmosphere organic molecules cannot form, and even if such molecules are brought in from outside, as has now been recognized[7], they are all too easily oxidised and destroyed.

Perhaps the most difficult problem to resolve in a purely terrestrial context, one that has not been adequately considered unto the present day, concerns the origin of the information content of life. The information needed to put life together, even in its simplest and most primitive form, is specific in kind and superastronomical in quantity. How was this highly specific information acquired in the first place from a situation that was initially thoroughly chaotic? The minimal number of random trials needed to discover the crucial molecular arrangements needed for life, as for instance in the enzymes, through random shufflings of the constituent amino acids, far exceeds anything that could happen in all the oceans of the Earth, let alone in Darwin's "warm little pond". The number of shufflings that is needed is superastronomically vast[8]. Transferring the problem to arrangements in a presumed RNA world does not alleviate the difficulties in any way. Nor does the hand-waving suggestion so often made that simple precursor systems emerged with relative ease and thereafter evolved into life through some ill-defined processes on Darwinian selection. To set the problem in its correct perspective let us suppose that a quarter of a million citizens of a certain city are each supplied with an unbiased cubic die, and suppose that we ask everyone at the stroke of midnight to throw their dice. The chance of finding life from random shufflings is similar to the chance of each one in the quarter of a million population simultaneously throwing a 'six' ! If honesty prevails one has therefore to admit that the ultimate origin of life is an event so improbable as to verge on the miraculous. So to constrain this event to our tiny planet is not only unnecessarily restrictive; it is pre-Copernican in philosophy. There is no logic whatsoever to demand that, and the largest available cosmic canvas is certainly to be preferred over the tiny planet that we happen perchance to inhabit.

Until the late 19th century panspermia had been taken to mean the passage of organisms through the Earth's atmosphere, not an incidence from outside. The Italian Lazzaro Spallanzoni who lived from 1729-1799 first discussed this form of panspermia. But almost a century before that, Fransesco Redi had carried out a classic experiment in the subject. He showed that maggots appear in decaying meat only when the meat is exposed to air, showing that whatever it was that gave rise to the maggots must have come to the meat through the air.

There was then a long wait until the 1860's when Louis Pasteur showed by his experiments on the souring of milk and the fermentation of wine that exactly similar results were relevant for microbes. Pasteur's classic experiments led him to the dictum that *life is always derived from life*. Pasteur's *life from life* dictum implied that each generation of every animal is preceded by a generation of the same animal. Several contemporary scientists of note, particularly physicists, considered the logical outcome of this view. Among them was John Tyndall, who lectured frequently on the London scene, as for instance in a Friday evening discourse at the Royal Institution on 21 January 1870, when he discussed the idea of microorganisms drifting through the air. It was to this lecture that the editorial columns of the newly established Journal *Nature* objected with some passion. Behind the objection was the realisation that were the Pasteur dictum taken to be strictly true, then the origin of life could not happen, here, or indeed anywhere.

This was put in the most succinct terms in 1874 by the German physicist Hermann Von Helmholtz[9]:

"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 (Lord Kelvin) said of 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 1881 meeting of the British Association in Edinburgh, Kelvin drew the following remarkably modern picture[10], advocating what could now be recognised as the theory of interplanetary 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[11], 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, as for instance the ability of microorganisms to survive inside a nuclear reactor. Many of these properties are of course highly relevant to survival in space.

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 pressure can have the effect of dispersing these particles throughout the galaxy. But 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.

An attack on Arrhenius' views was mounted in 1924 by P. Becquerel[12], on the basis of 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. On the whole microbiological research of the past 10 years has shown that bacteria and other microorganisms are remarkably space-hardy. Microorganisms are present at temperatures above boiling point in oceanic thermal vents; microbes are present in the Antarctic ices; they exist 8 kilometres below the earth's surface...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, this is very easily shielded against. A carbonaceous coating of only a few microns thick provides essentially total shielding against ultraviolet light, and there are several modern experiments that have demonstrated precisely that[12a].

Next, let's note that 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, permitting the original properties to be recovered, once the ultraviolet radiation has been shut off. Then, 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[12]. 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. Finally, experiments on bacteria within a nuclear reactor have demonstrated enzymic repair against actual DNA damage in cases where it is estimated that the DNA experienced as many as a million breaks in its helical structure, the breaks undergoing enzymic repair back to a fully viable form.

These are properties which Arrhenius did not know about and which obviously support his position very strongly. Nevertheless, bacteria and other microorganisms 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, must be subject to eventual destruction. Microorganisms expelled from any galactic source into unshielded regions of interstellar space will firstly become deactivated along the lines just discussed. 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. Table 1 shows a list of known interstellar molecules which is not complete, and to which should be added polyaromatic hydrocarbons (PAH's), the amino acid glycine and the molecule vinegar. Some if not all of these molecules could be interpreted as the degradation products of biology, as we shall shortly see.

INTERSTELLAR MOLECULES LISTED ACCORDING TO NO. OF ATOMS

2	3	4	5	6	7	8	9	10	11	13
H_2	H_2O	H_2CO	H_2C_2O	$HCONH_2$	HC_5N	$HCOOCH_3$	HC_7N	CH_3C_5N	HC_9N	$HC_{11}N$
CH	H_2S	H_2CS	H_2CNH	CH_3CN	$HCOCH_3$	CH_3C_3N	$(CH_3)_2O$	CH_3COCH_3		
CH^+	HCN	$HCNH^+$	H_2NCN	$[CH_3NC]$	CH_3C_2H		CH_3CH_2CN			
C_2	HNC	HNCO	HC_3N	CH_3OH	CH_2CHCN		CH_3CH_2OH			
CN	HCO	HNCS	HCOOH	CH_3SH	NH_2CH_3		CH_3C_4H			
CO	HCO^+	$HOCO^+$	C_3H_2	C_5H	C_6H					
CS	$[HOC^+]$	C_3H	C_4H							
NO	HCS^+	C_3N	SiH_4							
NS	[HNO]	C_3O	CH_4							
OH	N_2H^+	C_3S								
SiO	C_2H	NH_3								
SiS	OCS	H_3O^+								
SO	SO_2	C_2H_2								
SO^+	SiC_2	C_2H_4								
HCl	C_2S									
PN]	[NaOH]									
	$[H_3^+]$									

Table1

3. INTERSTELLAR ORGANICS

When two of the present authors first approached the subject of panspermia, they did so not from a biological point of view, but from an attempt to understand the nature of interstellar dust[13]. These cosmic dust grains populate the vast stretches of the Milky Way, showing up as a cosmic fog, dense enough in many directions to blot out the light of distant stars. The first thing to note was that these grains appear to be much the same in all directions, as we look outwards from the Earth. They are of a size that would be typical for bacteria, a micrometre or less.

Another fact that is perhaps of crucial importance in relation to panspermia is that the total mass of interstellar dust in the galaxy is as large as it possibly can be if 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 H,C,N,O present themselves as possible candidates. These would include water-ice, carbon dioxide, methane, ammonia, all these materials being easily condensible into solids at temperatures typically of about 20-50 degrees Kelvin, which is the usual temperature of the grains. During the decade starting from the early 1960's the properties of a wide range of inorganic grain models were studied, 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.

It was certainly a milestone in our progress towards 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 poymeric type[14]. Of course there are a vast number of possible organic compositions, making for a great number of further investigations that could be made. 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.

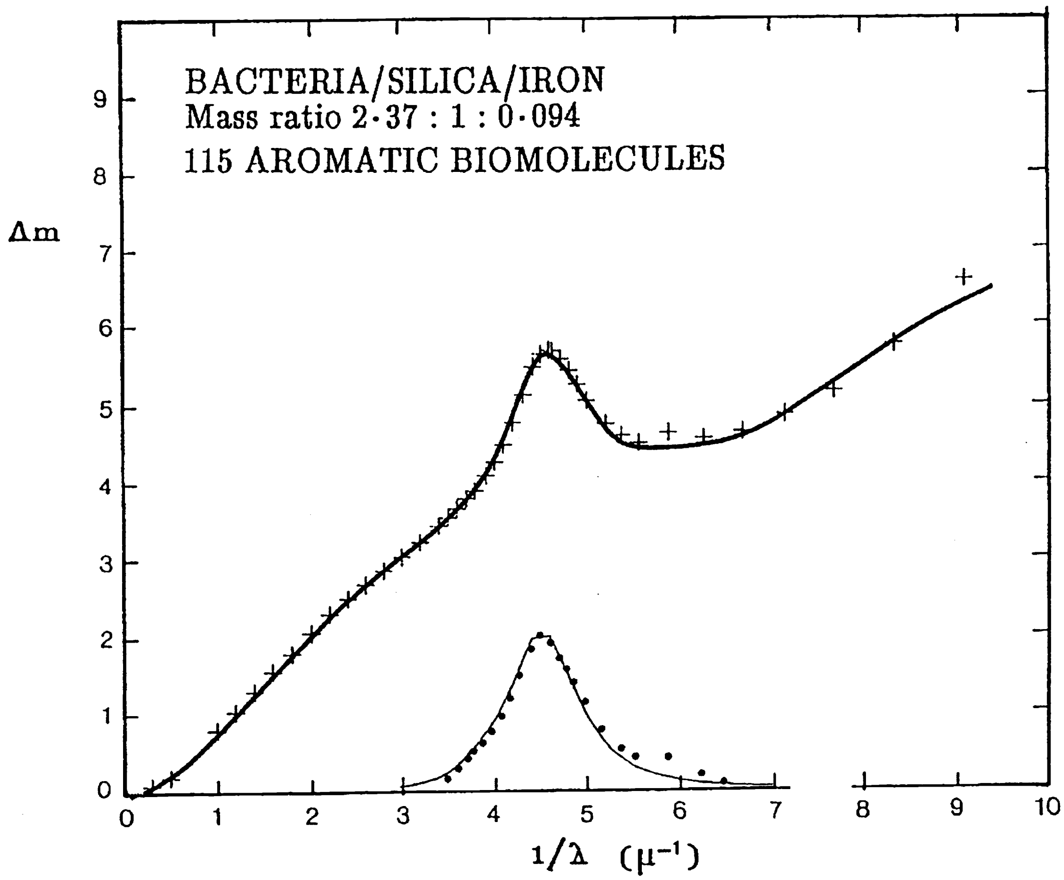

Figure 1. The filled circles (points) are excess interstellar absorption values over and above a scattering curve for hollow bacteria. Crosses are the mean interstellar extinction data. The heavy curve is calculated for hollow bacteria with and admixture of bioaromatic molecules and trace quantities of silica and iron in the form of submicron sized grains. The thin line is the absorption profile for an ensemble of bioaromatic molecules. (Full references and credits in Refs 13, 18)

Fig. 1 shows the so-called extinction curve of starlight, the way that starlight is dimmed as it travelled through clouds of interstellar dust. A puzzle here relates to how the visual part of this curve (over the 1 - 3 inverse micrometre range) could be reproduced almost exactly in all directions of the sky. For inorganic condensation models one requires a rather precise definition of particle sizes, and that is difficult to justify. The puzzle remained unresolved until we began to consider organic particles, particularly organic particles that were hollow. Particles that have about 70 percent hollow space gave very good results. This is what bacteria become when they are fully dried out. So now, a decade and a half after starting on this problem, two of the present authors decided in 1979 to test the hypothesis that the interstellar dust particles might really represent a graveyard of bacteria. The big attraction was that such tests could be carried out quite easily. One didn't have to draw up a catalogue of assumptions in making the calculations. One didn't need for example to *assume* a size distribution for our supposed bacterial particles. One could use a known bacterial size distribution, making the investigation without assumption on this and on a number of other issues as well. The result is shown as the solid curve in Fig. 1. This curve (heavy line) combines the effects of hollow bacterial particles with clusters of aromatic molecules that result naturally from the inevitable degradation of bacteria, along with a small admixture of silica-iron particles of submicron sizes that could explain the rise in the extinction into the far ultraviolet. Here at last was a good correspondence of the observational data points to the calculated expectation of a model, and it so happened that the model was of a bacterial nature.

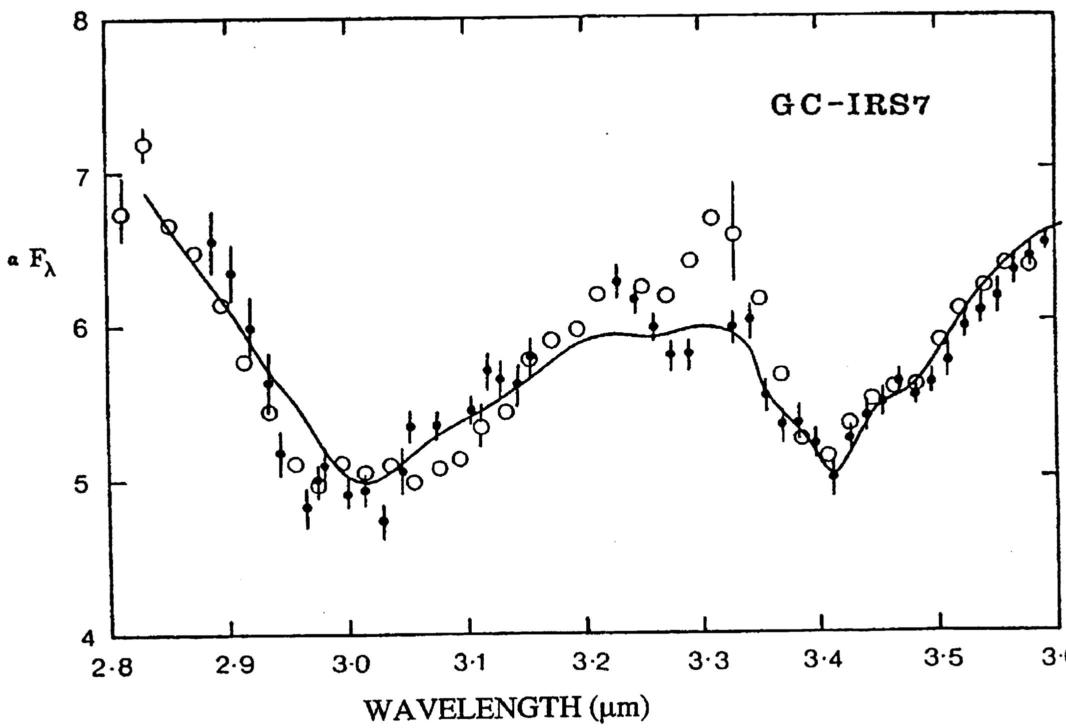

Figure 2. The agreement between an *E Coil* model (curve) and the flux data for the Galactic Center infrared source GC-IRS7. (Ref. 15).

Perhaps the most startling confirmation of the bacterial model followed the pioneering observations by D.T. Wickramasinghe and D.A. Allen[15] of the infrared source GC-IRS7. 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 as seen in Fig.2. A laboratory spectrum of the desiccated bacterium *E. Coli*, obtained some months *earlier* by S. Al-Mufti, together with a simple modelling procedure provided a close point by point match to the astronomical data over the entire 2-4 micron waveband, as seen here. At this stage there was no alternative but to face up to the somewhat startling conclusion that a large fraction of the interstellar dust *must* spectroscopically at least be indistinguishable from freeze-dried bacterial material.

It has often been claimed that a curve like the one in Fig. 2 could be obtained from non-biologically derived organic materials in many ways. Such a possibility cannot be denied, although to this day a competing fit using a *clearly defined and easily reproducible* organic mixture has not been found. Some elaborate laboratory procedures, involving carefully controlled irradiation of inorganic mixtures, have yielded undefined "organic residues" that possess some of the desired properties, but the relevance of these experiments and experimental conditions to an astronomical situation could be questioned with some justification.

Another remarkable development in recent years has been the discovery of vast quantities of aromatic molecules; molecules based on hexagonal carbon-ring structures. These molecular structures appear to be distributed quite extensively on a galactic as well as an extragalactic scale, and once again a large fraction of the available interstellar carbon seems to be tied up in this form. Needless to say, such molecules are part and parcel of biology, and their occurrence in interstellar space is readily understood as arising from the break-up of bacterial cells.

Even much earlier, in 1962, the presence of aromatic molecules in space might have been inferred from the so-called diffuse interstellar absorption bands. It has been known for over half a century that some 20 or more diffuse absorption bands appear in the spectra of stars, the strongest being centred on the wavelength 4430A. Despite a sustained effort by scientists over many years no satisfactory inorganic explanation for these bands has emerged. In the early 1960's F.M. Johnson[16] showed that a molecule related to chlorophyll - magnesium tetrabenzo porphyrin - has many of the required spectral properties. Chlorophyll of course is an all important component of terrestrial biology - it is the green colouring substance of plants, the molecule responsible for photosynthesis, the process that lies at the very base of our entire ecosystem on the Earth.

There is yet another property of biological pigments such as chorophylls that persistently shows up in astronomy. Many biological pigments are known to fluoresce, in the fashion of pigments in glowworms. They absorb blue and ultraviolet radiation and fluoresce over a characteristic band in the red part of the spectrum. For some years astronomers have been detecting a broad emission feature of interstellar dust over the waveband 6000-7500 Angstroms. Chloroplasts containing chlorophyll, when they are cooled to temperatures appropriate to interstellar space fluoresce precisely over the same waveband[17].

In this article we have discussed only a small subset of the astronomical data that since the 1980's have appeared to point consistently to in the direction of panspermia. At the most conservative the astronomical data show decisively the overwhelming dominance of highly complex organic molecules in a condensed state. On this there is no longer any disagreement. Also isotropy of visual extinction curve of starlight shows that these organic grains must be substantially the same in one direction from the Earth as in another. By far the simplest way to produce a vast quantity (10^{40} grams) 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.

4. COMETS

The next question to be addressed is: where did the interstellar organic particles come from? How did they get where we now observe them to be? And this in turn leads us to another important step along the path towards panspermia, to the comets.

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 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 particles, typically at a rate of a million or more tons a day. This was what Comet Haley 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. Fig. 3 shows the infrared emission spectrum of dust from Comet Haley obtained by D.T. Wickramasinghe and D.A. Allen compared with bacterial and abiotic organic models. We note that a bacterial model gives a significantly better fit. The analysis of dust impacting on mass spectrometers aboard the spacecraft Giotto also leads to composition of the dust that are exceeding complex and organic and fully consistent with the biological hypothesis. (See ref. 18 for full list of references and more details). Largely similar conclusions have been shown to be valid for other comets as well including Hyakutake and Hale-Bopp. Thus one could conclude that cometary particles, just like the interstellar particles, are *spectroscopically* identical to bacteria.

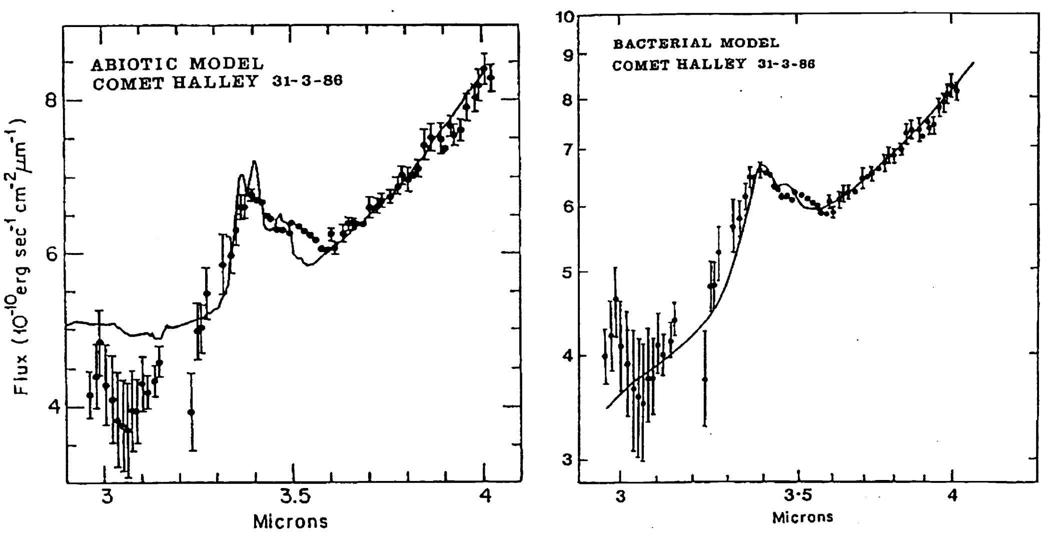

Figure 3. Observational data for dust released from Comet Halley (points) compared with predictions for abiotic and bacterial dust models.

The radiation pressure from sunlight drives small particles expelled from comets rapidly outwards in the solar system, and ultimately out into interstellar space. This is exactly what is happening when we observe the tails of comets. The dust tails consist of small organic particles, expelled rapidly outwards by sunlight. So this is how the organic particles get out from comets into interstellar space. They are sprayed out from a great multiplicity of events like that which occurred to Comet Halley in March 1986, like all the cometary explosions that supply the materials of the comas and tails of comets.

Comets are believed to have formed already in the early stages of the condensation of the sun. Here we reach a delicate point in our argument. We require some small fraction of microorganisms present in the parent solar nebula to have retained their viability. Or to be capable of being reactivated after becoming incorporated in comets. The fraction could be exceedingly small, however. For one percent of the mass of the initial comet cloud being made up of interstellar dust the total number of "graveyard bacteria" included within a single comet would be some 10^{28}. A viable fraction as small as one part in 10^{17}, would still yield a hundred billion bacteria for each comet to start life with. That is of course vastly more than enough. Once replication starts inside a newly-formed comet, all previous losses become irrelevant, because of the enormous capacity of even a single viable cell to multiply, as we have already seen.

But replication requires heating so as to produce liquid water. The cloud in which the solar system formed would be expected to have harboured one or more massive stars of the types that produce the unstable isotope ^{26}Al with a half-life of three-quarters of a million years. This gives long enough time for the solar nebula to form, and to condense before all the ^{26}Al is effectively gone. Because ^{26}Al is a major source of the stable isotope of magnesium, ^{26}Mg, which was a common element in the solar nebula, the original amount of ^{26}Al must then have been substantial. In primitive cometary condensations, ^{26}Al would be expected to make up a mass fraction of about one tenth of a percent, or less, according to the time which elapsed since its stellar synthesis.

It can be easily shown that the energy released in the radioactive decay of Al-26 is more than enough to maintain a warm liquid interior in comets for a million years or more. There is good reason to believe therefore that the early comets were indeed liquid.

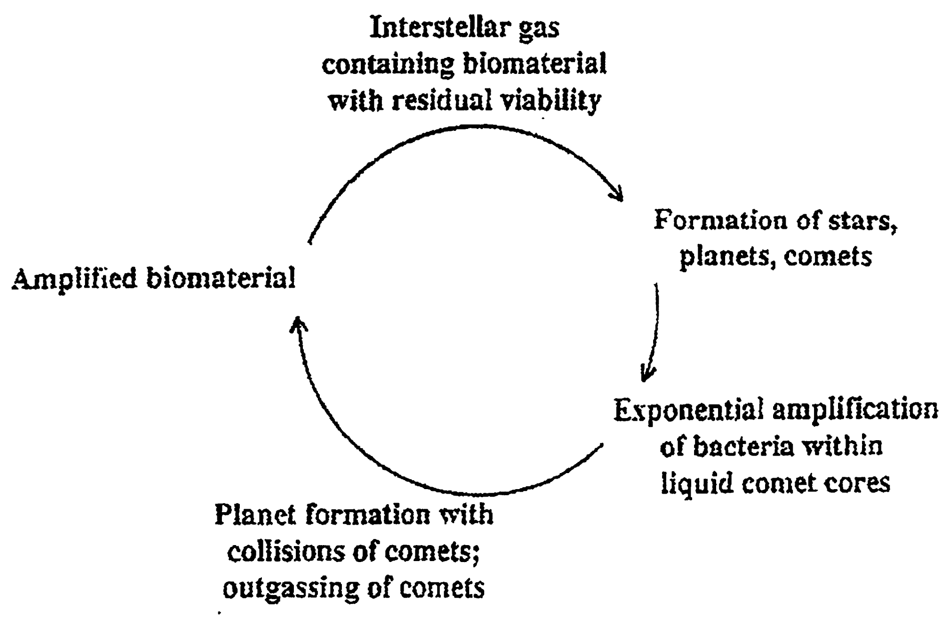

Figure 4. Cosmic amplification cycle

So it turns out that the comets are the viable places of replication of microorganisms - or more accurately they are among the more probable places of replication, leading to the cosmic amplification cycle of biology shown in Fig. 4.

5. MARS

We next turn to some tests of panspermia that might be contemplated at the present time. First consider Mars, the only planet outside the Earth where one might expect life to be able, even barely, to survive at the surface. NASA carried out a search for primitive life forms such as bacteria in 1976. Two spacecraft Viking 1 and Viking 2 arrived at chosen spots on the Martian surface equipped to make *in situ* tests for bacterial life. In one experiment a nutrient broth (with a radioactive label) of the sort that is normally used to culture terrestrial bacteria was poured onto a sample of Martian soil, and gases were found to froth out as would be consistent with the presence of microbial life. However, another experiment involving mass spectroscopy to look for organic residues left by bacteria produced a negative or equivocal result.

In 1976 NASA made the pronouncement that the Viking experiments did not support the presence of bacterial life on Mars. Such a result accorded with the reigning paradigms, and so the matter may well have rested, but it did not. In 1986 a careful re-examination of the same data combined with nearly a decade of laboratory experimentation led to the startling conclusion that primitive life could well exist in subsurface niches on this planet[19]. Not only was it the case that the Viking experiments were not tested beforehand on the most inhospitable terrain on the Earth - the dry valleys of the Antarctic - until well after 1976, but when they were so tested results identical to the Martian results were obtained[19]. The Antarctic dry valleys surely harbour vast populations of microorganisms, but their turnover rate is so small that no organics were detectable by the Viking instruments. Levin and Straat[19] further concluded that all attempts mimic the Martian results using non-biological models were unsuccessful. Now, as then, the results of the Viking experiments of 1976 remain consistent with the presence of microbial life on Mars, although they do not prove it.

6. METEORITE MICROFOSSILS

Before coming to the most recent claims of microbial fossils in a Martian meteorite let's return to Earth and look first at earlier claims of a similar kind that had either been dismissed or ignored. In the mid-1960's H. Urey, and later G. Claus, B. Nagy and D.L. Europa[20] 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 constriction of 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 came to be included within carbonaceous meteorites. This question could not be satisfactorily answered at the time 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 may have contained microbial life thriving within subsurface pools. Carbonaceous chondrites can thus be thought of as fragments of biological comets that have been stripped of volatiles, and within which sedimentation and compaction of microorganisms may have occurred over hundreds of perihelion transits.

In the early 1980's the German paleontologist H.D. Pflug[21] 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 be excluded by virtue of the techniques used. No convincing non-biological alternative to explain all the features were forthcoming, although the statement that they were all mineralogical artifacts that somehow trapped organics from a surrounding medium came to be widely publicised.

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 a carbonaceous structure discovered by Bradley et al[22] with a microbial fossil found in the Gunflint cherts of N. Minnesota (See Fig. 5) we noted already in 1985 (Hoyle et al[23]) that a biological explanation (a partially degraded iron-oxidising bacterium) is the most plausible.

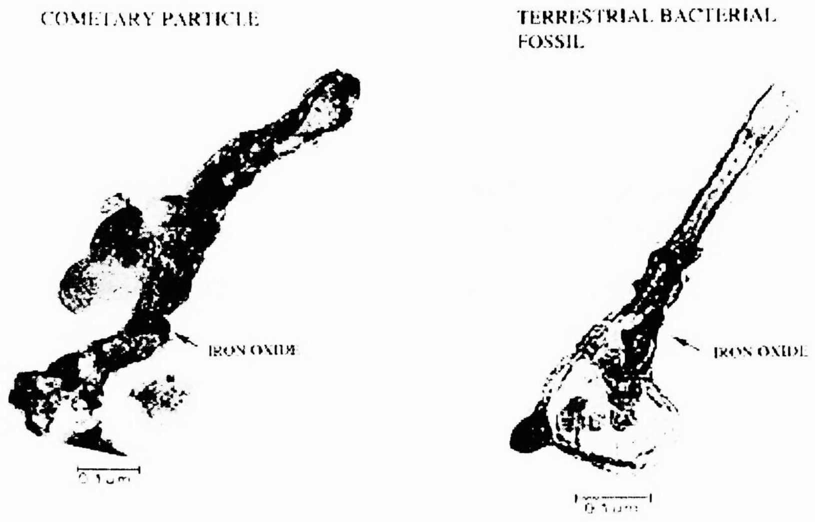

Figure 5. Comparison of a terrestrial fossil bacterium with a carbonaceous structure recovered in cometary debris (Ref. 22, 23)

In 1993 further studies by S.J. Clemett[24] 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 possibly biogenic. A final and unequivocal proof of the biogenicity of cometary particles would, in our view, follow from NASA's Stardust Project, which is a decade away, in which cometary material will be retrieved.

7. THE ALH 84001 SAGA

The latest chapter in the exploration of panspermia was opened in August 1996 with studies of a 1.9kg meteorite (ALH 84001) which is believed to have originated from Mars[25]. 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[25] have found that within the meteorite ALH 84001 there are sub-micron sized carbonate globules around which complex organic molecules are deposited. These molecules, including polyaromatic hydrocarbons, are characteristic products of the degradation of bacteria. 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 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 still 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 defend their original conclusion and are advancing even stronger arguments and evidence. 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 3600 my 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.

8. BIOLOGICAL EVIDENCE ON EARTH

Along with the accumulation of astronomical evidence supporting panspermia there has also been evidence from geology and terrestrial biology 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 severely pumelled by comet and meteorite impacts[26]. This evidence comes in the form of a slight enhancement 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. The primordial soup, if there was one, is now required to operate under the harshest of conditions in circumstances where the survival of organic molecules, let alone life is in doubt. Cometary impacts are now being invoked to deliver the components of the primordial soup, as well as the water that went to form the primitive oceans. It would seem much more likely in our view that comets may also have brought microbial life in a fully-fledged form.

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 our genes, 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 an ancestral microbe, we believe.

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 the number of bacterial species is estimated as many millions, even billions[27]. The existence of this truly vast number has been inferred indirectly from RNA and DNA studies, and most have not even yet been cultured, and perhaps never will. It appears that many of these microbial species are what are called "extremophiles", bacteria that appear to seek extreme and hitherto uncharted environments[28]. 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.

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 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[29]. 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 putative 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 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 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 could be no more to it than that!

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[31-32]. Other reports show that genes required by more highly evolved species may reside without apparent function in the genomes of prokaryotes[33] or viruses[34]. One cannot help but notice that these findings corroborate the concept of cosmic bacteria and cosmic geners that two of the present authors have advocated for over two decades. It might well be that an emergent cosmic worldview for the new millennium would include the recognition that microorganisms are not just our cosmic ancestors, but that they are the inheritors of the Universe as well.

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