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Cryobiology 48 (2004) 113–125
CRYOBIOLOGY
www.elsevier.com/locate/ycryo

The universe: a cryogenic habitat for microbial life[☆]

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Received 29 September 2003; accepted 4 March 2004

Abstract

Panspermia, an ancient idea, posits that microbial life is ubiquitous in the Universe. After several decades of almost irrational rejection, panspermia is at last coming to be regarded as a serious contender for the beginnings of life on our planet. Astronomical data is shown to be consistent with the widespread distribution of complex organic molecules and dust particles that may have a biological provenance. A minuscule (10^{-21}) survival rate of freeze-dried bacteria in space is all that is needed to ensure the continual re-cycling of cosmic microbial life in the galaxy. Evidence that terrestrial life may have come from elsewhere in the solar system has accumulated over the past decade. Mars is seen by some as a possible source of terrestrial life, but some hundreds of billions of comets that enveloped the entire solar system, are a far more likely primordial reservoir of life. Comets would then have seeded Earth, Mars, and indeed all other habitable planetary bodies in the inner regions of the solar system. The implications of this point of view, which was developed in conjunction with the late Sir Fred Hoyle since the 1970s, are now becoming amenable to direct empirical test by studies of pristine organic material in the stratosphere. The ancient theory of panspermia may be on the verge of vindication, in which case the entire universe would be a grand crucible of cryomicrobiology.

Keywords: Panspermia; Comets; Interstellar dust; Microorganisms

On the surface of the Earth many types of microorganisms live either close to the freezing point of water, or very near the water–ice interface. Psychrophilic and psychrotophic microorganisms—archaea, bacteria and algae—abound in the polar caps, and in permafrost. Freeze-dried microorganisms have been recovered from permafrost and from the depths of Lake Vostok, and cultured in the laboratory after lying dormant for 10–20 million years.

The wider universe outside the Earth would, however, appear the most natural home for cryomicrobiology. In the outer regions of the solar system, in the planets Uranus and Neptune and in a 100 billion comets, over 100 Earth masses of ices and organics exist. The comets spend most of their lives deep frozen at temperatures below 50 K, but at the time of their formation 4.5 billion years ago their inner cores would have been melted due to the release of radioactive heat, thus providing an environment for microorganisms to grow. A few comets approach every year to within about the Earth's orbital distance from the sun. At such times they are sufficiently warmed at their surfaces

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[☆] This work was funded by the Astrobiology Research Trust, Memphis, Tennessee, USA.

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0011-2240/$ - see front matter © 2004 Published by Elsevier Inc.
doi:10.1016/j.cryobiol.2004.03.001

to produce transient episodes of subsurface melting. Similar periods of warming and melting can also occur further out in the comet's orbit, when it is struck by smaller objects that could trigger the release of subsurface chemical energy, which may involve the exothermic recombination of trapped free radicals. Biological replication can then transiently resume.

Throughout most of the solar system carbonaceous material is locked in a hard frozen state. Even on the Earth, warm interglacial periods, such as the one we now enjoy, constitute only a 10th of the duration of more protracted epochs of glaciation, so cryogenic survival strategies must become crucial for the preservation, and continuation of life.

Outside the solar system, microorganisms exposed to the near vacuum conditions in interstellar clouds would inevitably become desiccated and take up temperatures typically in the range 10–30 K. They would remain thus in a dormant freeze-dried state until such time as they find themselves in environments where they can replicate—within newly formed comets, or upon planetary surfaces.

Origin of life models

The standard theory for the origin of life begins with a primordial atmosphere on the Earth in which the synthesis of the chemical building blocks of life (e.g., amino acids) from inorganic gases occurs through the action of solar ultraviolet radiation and electric discharges. Organic molecules so formed are then supposed to rain down into the primitive oceans producing a dilute soup. In such an exceedingly dilute solution reaction rates would be minimal and biochemistry hard put to produce all the complex chemical transformations needed for an origin of life. It is therefore proposed that evaporation of water from shallow lakes and ponds, and at the margins of the sea led to sufficient concentrations of organics for prebiotic chemistry to proceed, and after millions of years a self-replicating living cell is postulated to arise. Similar processes are discussed nowadays in the context of undersea black smokers leading to the possible origin of thermophilic microorganisms. All such mechanisms are essentially variants of the original model proposed by Oparin [27] and Haldane [12], which was at least partly vindicated by the work of Miller [25] 50 years ago. The formation of the chemical building blocks of life was demonstrated, but the further steps leading to life remained elusive.

The highly specific and exceedingly intricate complexity of living organisms at a molecular level is self-evident, and it is clear that no significant progress has been made in 50 years towards understanding how the information gap between a non-living mixture of organic molecules and life could be achieved. For instance Margulis (quoted in [15]) has stated that to proceed "…from a bacterium to people is less of a step than to go from a mixture of amino acids to that bacterium." Moreover we have no definite knowledge by which we can assert that this step ever happened on the Earth—namely that a de novo origin was localised to a tiny speck of 'cosmic dust' that is the Earth. The superastronomical information gap between non-life and life provides, in the view of the author, the main justification for considering theories of origin that involve the universe as the whole. The final information content of life could have been arrived at by a cumulative addition of truly minuscule probabilities in self-replicable partial stages that are repeatedly and serially impressed on a vast cosmic system. This process must be envisaged to take place over cosmological timescales, and to involve the resources of all the stars in all the galaxies in the entire universe.

Rationale for panspermia theories

There is no logic that demands an origin of life on the Earth. The fact that life is found on the Earth does not mean that life necessarily started here. The Celtic languages are spoken in Wales—but these languages did not originate in Wales, they came from mainland Europe many thousands of years ago. The same logic could be true of life.

The Earth is by no means disconnected from the wider Universe. We do not live on a planet enclosed in a closed box sealed away from cosmic contaminants. Even today cometary organic molecules arrive here plentifully, at an average rate of several tonnes per day. Thus a chain of connection:

$$\text{Earth} \rightarrow \text{Comets} \rightarrow \text{Presolar nebula} \rightarrow \text{Interstellar clouds} \rightarrow \text{Stars} \rightarrow \text{Galaxy} \rightarrow \text{Universe can be envisioned.}$$

Living material contains about 20 different types of atoms, the most important being hydrogen, carbon, nitrogen, oxygen, and phosphorus. The ultimate source of origin of these chemical elements is stellar nucleosynthesis—the process by which the primordial element H is converted first to He and thence to C, N, O, and heavier elements in the deep interiors of stars. Thus, at the level of the constituent atoms we are indisputably creatures derived from the cosmos.

From the 1970s onwards, astronomers discovered a host of organic molecules in interstellar clouds, and since 1986 similar molecules were also found in comets. These discoveries prompted Fred Hoyle and the present author [17,19] to re-examine the ancient theory of panspermia, which posits that life is a cosmic phenomenon, and that life on Earth is derived from a vast cosmic system.

History of panspermia

The basic concepts underlying panspermia have had a history spanning many centuries and many cultures. In most ancient philosophies of the Orient—for instance in Vedic and Buddhist writings—the cosmic nature of life is taken for granted. Life is regarded as an inherent property of a Universe, one that is itself infinite, timeless, and eternal.

Louis Pasteur's classic experiments [29,30] in the 1850s and 1860s, in which he showed that microorganisms are always derived from pre-existing microorganisms, provided perhaps the most important experimental basis for panspermia. Indeed this was a conclusion that was reached quite early in 1874 by the German physicist Hermann Von Helmholtz [35]:

> 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 [34] (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..."

The next noteworthy proponent of panspermia at the dawn of the 20th century was the Swedish Chemist Svante Arrhenius [2]. In 1908 Arrhenius noted 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 for taking seeds down to temperatures close to 0 K, and of then demonstrating their viability when reheated with sufficient care. Arrhenius conceived of microorganisms travelling individually through the galaxy from star system to star system. He noticed that organisms with critical dimensions of 1 μm or less are related in their sizes to the typical radiation wavelengths from dwarf (sun-like) stars in such a way that radiation (light) pressure can have the effect of dispersing these particles throughout the galaxy.

The ultraviolet problem

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 20th century. Becquerel [3] criticised panspermia on the basis of possible ultraviolet damage of space-travelling microbes, and similar criticisms were repeated ever since, even in modern times [24]. These arguments are either flawed or highly insecure, however. Even under normal laboratory conditions microorganisms are not readily killed by ultraviolet, they are mostly deactivated due to the dimerization of pyrimidine bases. No genetic information is lost in the process and in many instances the damage can be repaired by the operation of specialised enzymic systems. Dimerization of bases distorts the DNA configuration and has the effect of impeding transcription. Exposure of UV irradiated bacteria to visible sunlight is known to promote repair. So also does the holding of ultraviolet-irradiated cells in the dark in non-nutrient buffers, the repair in this case being mediated by the operation of a 'dark repair' mechanism.

No data exists at the present time relating directly to the effects of ultraviolet irradiation on bacteria under cryogenic conditions and in the absence of air and water, conditions such as would apply in interplanetary, or interstellar space. It should also be pointed out that microorganisms are easily shielded against ultraviolet light. Indeed molecular clouds in the galaxy are highly effective in this respect, both in cutting out the glare of ultraviolet radiation and permitting the growth of protective mantles around bacterial particles. Thin skins of carbonised material around individual bacteria, only 0.02 μm thick, would also effectively block the damaging ultraviolet light [39].

Ionising radiation and extreme hardyhood of bacteria

On the whole microbiological research of the past 10 years has shown that microorganisms are remarkably space-hardy. Thermophiles are present at temperatures above boiling point of water in oceanic thermal vents, and as we have already pointed out, entire ecologies of psychrophilic and psychrotrophic microorganisms are present in the frozen wastes of Antarctica. A formidable total mass of microbes also exists at great depths in the Earth's crust, some 8 km below the surface, greater than the biomass at the surface [10]. A species of phototrophic sulfur bacterium has been recently recovered from the Black Sea that can perform photosynthesis at exceedingly low light levels, approaching near total darkness [28]. There are bacteria (e.g., *Deinococcus radiodurans*) that thrive within the cores of nuclear reactors [32]. 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.

Most modern objections to panspermia have been based on arguments relating to cosmic ray survival [24]—it being claimed that cosmic ray exposures in space over hundreds of thousands of years would prove fatal for microorganisms. These criticisms are again insecure and, moreover, fail to take account of the fact that the replicative power of bacteria is so great that only a minute ($\sim 10^{-21}$) survival is required at each regeneration site between periods of freeze-dried dormancy in the interstellar medium.

Ionising radiation limits viability by dislodging electrons, causing bond breaks in the DNA, and by forming reactive free radicals. The radiation doses that seriously compromise viability in cultures depend critically on the particular bacterial species, and as mentioned earlier some species such as *B. subtlis* and *D. radiodurans* are more resistant than others. In vegetative cultures, under laboratory conditions, doses equivalent to 2 Mrad have been found to limit residual viability of *Streptococcus faeciuim* by a factor of 10^{-6} [7], whereas similar doses have little, or no effect on cultures of *D. radiodurans* or *Micrococcus radiophilus* [22].

The doses of ionising radiation received by a bacterium in interplanetary space within the solar system depends on distance from the sun and the phase of solar activity, being highest at times near the peak of the solar sunspot cycle. In a recent NASA/LDEF (Long Duration Exposure Facility) experiment, direct exposure of spores of *B. subtilis* to unshielded solar radiation for 2107 days was found to lead to significant rates of survival [16]. The survival of common species of bacteria near the Earth's orbit for about a decade therefore seems well-attested.

The dose of cosmic rays received by a naked bacterium in a typical location in interstellar space, over a timescale of a million years, can at present be only very poorly estimated. It is possibly in the range 10–45 Mrad per million years. Doses of this order are of course higher than the doses that have been delivered to laboratory cultures where survival is well-attested. Yet the exposure conditions in space, where two successive cosmic ray ionising events are separated by about 100 years, would be dramatically different from those pertaining to the laboratory experiments.

Most of the data on irradiation of bacteria have been obtained in the context of food sterilization. It is found that the oxidising effects of free radicals, particularly OH^- causes over 90% of DNA damage, and so reducing H_2O content would drastically reduce the lethal effects of ionising radiation. Ionizing radiation delivered under anaerobic conditions with low O_2 pressures is also found to diminish DNA damage. Low temperatures also go in the same direction by immobilising and preventing the diffusion of free radicals. Much more work is urgently needed to be done by cryobiologists to resolve these important issues.

A low flux of ionising radiation in space delivered over astronomical timescales to dormant freeze-dried bacteria (in the absence of H_2O and air) would perhaps bear no comparison with equivalent doses on vegetative cultures in the laboratory. The nearest terrestrial analogue might be for microbial spores that have been exposed to the natural radio activity of rocks for geological timescales. Indeed viable cultures of bacteria have been recovered from ice drills going back 500,000 years, from isolates in amber over 25–40 million years [6,21], and from 120 million-year-old material [11]. Similarly bacteria have been recovered in salt crystals from a New Mexico salt mine dated at 250 million years [36]. The present day dose rate of ionising radiation on the Earth arising from natural radioactivity is in the range 0.1–1 rad per year. These well-attested recoveries of dormant bacteria/spores after 10^8 years must therefore imply tolerance to ionising radiation with total doses in the range $\sim$10–100 Mrad.

Interstellar organic molecules

Notwithstanding the remarks of the previous sections some fraction of cosmic bacteria which have no protective coatings and which are exposed remorselessly to cosmic rays and to the background of starlight in unshielded regions of interstellar space would be subject to degradation and eventual destruction. 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 the degradation of biology, biologically generated fossil fuels in this case, cosmic microbiology in the interstellar clouds. The theory of cosmic panspermia that we propose leads us to argue that interstellar space serves both as 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.

Interstellar dust

My own interest in panspermia began with attempts to understand the nature of cosmic dust [18]. Interstellar 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 dust grains can be shown to be of a size that would be typical for a bacterium, a micrometre, or less.

A fact that impressed me 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, and O in combination with hydrogen present themselves as possible candidates. These include water ice, carbon dioxide, methane, ammonia, all such materials being easily condensable into solids at temperatures typically of about 20–50 K, which is the average temperature of the dust grains in space. During the decade starting from the early 1960s Fred Hoyle and I 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.

It was a milestone in our progress towards interstellar panspermia when I realised that there is another very different class of materials that can be made from the same four commonest elements—C, N, O, and H, namely organic materials, possibly of a polymeric type [37]. Of course there are a vast number of organic compositions that are possible, making for a great number of further investigations that could be done. By the mid-1970s, the astronomical observations were spanning a large range in wavelength, from 30 μm in the infrared, through the near infrared, into the visible spectrum, and further into the ultraviolet. So a satisfactory theory of the nature of interstellar dust grains had by now to satisfy a very large number of observational constraints.

In 1979 Fred Hoyle and I stumbled on a result that led to many further discoveries, all of which pointed in the direction of panspermia. As already noted bacterial grains in interstellar space would be freeze-dried. Freeze drying in a vacuum (as exists in space) would ensure that free water in the cell diffuses out of the porous cell wall leading to the development of cavities as shown schematically in Fig. 1. (This would be different from rapid freezing in air when the external pressure could lead to the partial collapse of cell walls.)

The volume of the final vacuum cavity for a typical bacillus amounts to about 60% of the total, and the resulting average refractive index of the entire structure is readily calculated as having a value equal to 1.16. Next we require a distribution of sizes for the bacteria, which was available in the literature for spore-forming microorganisms (see Fig. 2).

When the extinction behaviour of this ensemble of freeze-dried bacteria was calculated, the result compared with the astronomical data on the dimming of starlight is shown in Fig. 3.

I was indeed dumbfounded to find a result so good after so many years of failure to obtain a satisfactory fit using highly contrived inorganic models. Once the proposition is made that "interstellar grains are bacteria" there is no further

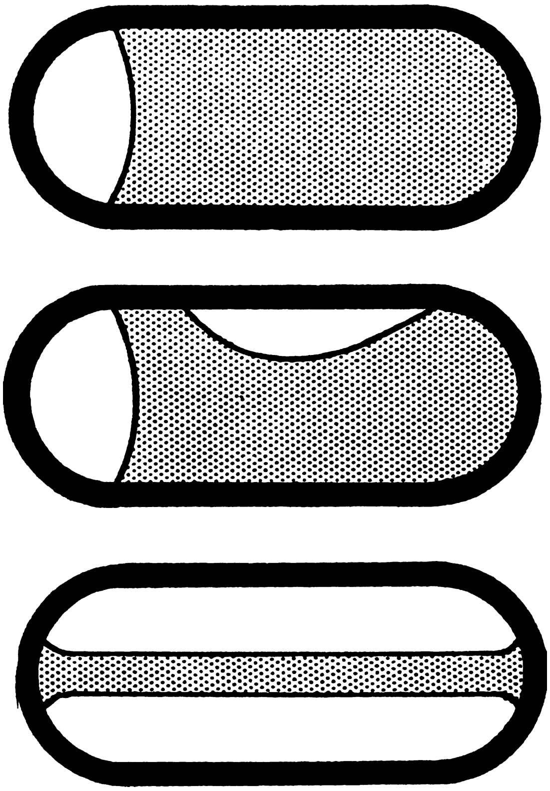

Fig. 1. Schematic stages in the freeze drying of a bacillus. White area represents empty space.

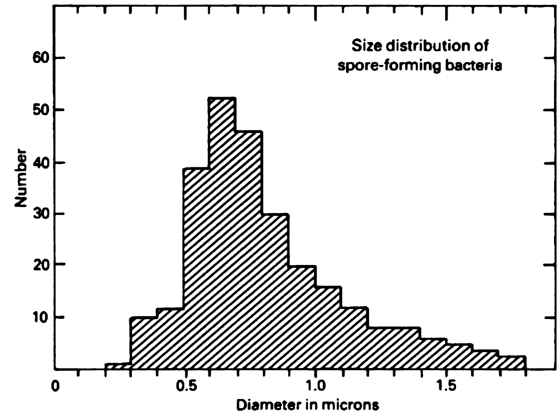

Fig. 2. Histogram of diameters of spore forming bacteria.

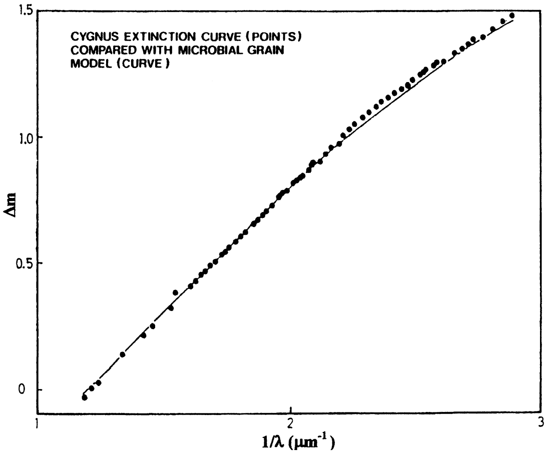

Fig. 3. Bacterial extinction over the visible spectrum compared with interstellar extinction data.

room for maneuver—the model is completely defined. But for the astronomical data further in the ultraviolet another refinement was required. Added to the bacterial population we need two further components derived from biology: non-hollow viruses and/or nanobacteria contributing 29% to the total mass, and free biological aromatic molecules, which would be the most stable subunits, and molecules to result from the degradation of unshielded bacteria in space. The combination of these components leads to the curves depicted in Fig. 4.

Perhaps the most startling confirmation of the bacterial model followed the observations [1] 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 μm wavelength region, indicative of combined CH, OH, and NH stretching modes. A laboratory spectrum of the desiccated bacterium *Escherichia coli*, together with a simple modeling procedure [18] provided an exceedingly close point-by-point match to the astronomical data over the entire 2–4 μm waveband (Fig. 5).

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} ton.

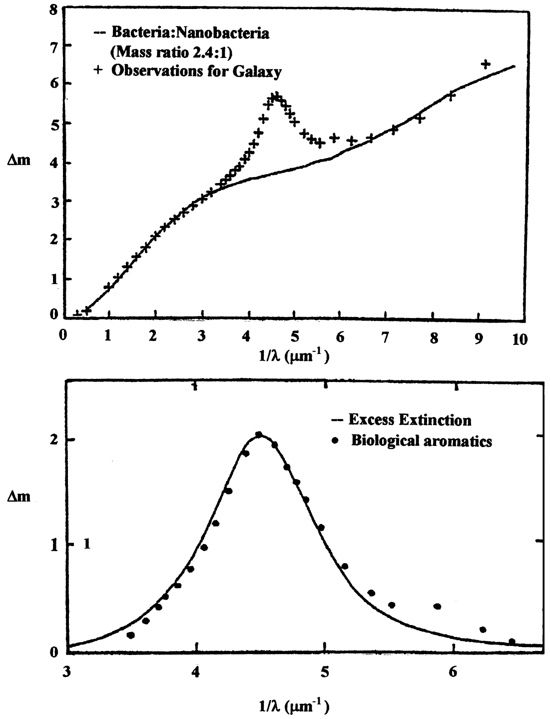

Fig. 4. Top: Interstellar extinction data over the wavenumber range 0.2–10 μm^{-1} compared with scattering by freeze-dried bacteria and nanobacteria. Bottom: Excess extinction over the mid UV band compared with absorption by an ensemble of biologically derived aromatic molecules.

Replication in comets

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 2–3 h. A continued cascade of doublings with unlimited access to nutrients would lead to a culture that enveloped the interior of a 10 km radius comet in less than a week. No abiotic process remotely matches this replication power of a biological template. Once the immense quantity of organic

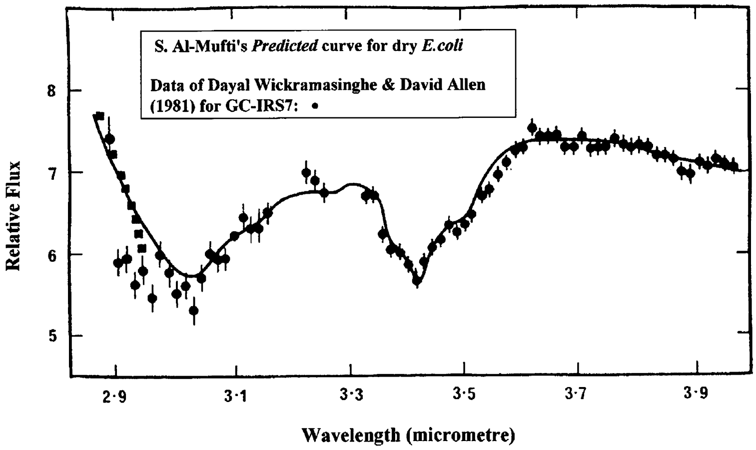

Fig. 5. Infrared spectrum of GC-IRS7 compared with bacterial model.

material in the interstellar material is appreciated, a biological origin for it becomes an almost inevitable conclusion.

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} g. 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} g, 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? At the point of their origin, comets would have acquired not only a compliment of interstellar bacteria but also organic molecules and radicals, and radiogenic nuclides such as ^{26}Al formed in a nearby supernova. Radiogenic heating then maintains a warm liquid interior for close on a million years, and this is enough for bacterial replication to operate. Even the smallest numbers of viable chemotrophic bacteria would replicate to swamp the liquid core of the primitive comet. When such a comet re-freezes the bacterial cells will become frozen.

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. 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 [38]. 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 viable bacteria (less than one in 10^{21}) that retain viability despite the harsh radiation environment of space. When a new star system (e.g., 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 viable 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. 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.

Microfossils in meteorites

In the mid-1960s H. Urey, and later Claus et al. [8] 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.

In the early 1980s the German paleontologist Pflug [31] 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 intact. 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 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 [13,14].

The Martian 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 [23]. ALH 84001 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.

McKay et al. [23] 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 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, until Colin Pillinger and his team have completed their in situ analysis of organics on the Martian surface perhaps with the landing of Beagle 3.

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 3.6 billion years before the present. 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 (the idea that comets replicate and transfer cosmic microbiology) it would appear likely that both the Earth and Mars came to be seeded with bacterial life at the same time.

Oldest life on Earth

Along with the accumulation of astronomical evidence supporting panspermia in one form or another there has also been evidence from geology. The earliest evidence for terrestrial life has now been pushed back beyond 3.83 billion years before the present, well into an epoch when we know for certain that the Earth was severely pummeled 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. 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 transferring 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 [10], such as we now have, would easily have been generated. So also could microbial life in deep sea thermal vents be explained as representing a primordial habitat that accommodated the most heat resistant of the microbes that arrived from space.

More evidence of microbiology outside the Earth

We have discussed earlier how modern microbiology has yielded a wealth of new discoveries relating to 'unearthly properties' of microorganisms. 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 growing evidence of its subsurface oceans beneath a frozen crust, provides many opportunities for a highly developed microbiota. Life may even be present in the clouds of Venus. Whilst the surface of Venus is too hot to sustain life, there is an intriguing possibility of an aerobiology thriving in the Venusian clouds. Dirk Schulze-Makuch and his colleagues have recently pointed out that 30 miles above the surface there are droplets of water and chemical tell-tale signs of life. They had expected to find high levels of carbon monoxide, but instead found hydrogen sulphide and sulphur dioxide, gases normally not found together and also carbonyl sulphide, a gas so difficult to produce by inorganic chemistry that it is generally considered to be a marker for living organisms. Likewise with new evidence of liquid water on Mars, there could be plenty of scope for microbial life in secluded subsurface niches.

According to theory described in this paper life on Earth began with the introduction of microorganisms from comets. It is clear, however, that this process could not have stopped at some distant time in the past. Comets have been with us throughout, and the Earth has continued to plough through interplanetary and cometary dust. 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, nanobacteria, and smaller particles such as viruses and viroids. It is well known that viral genes sometimes come to be included in the genomes of cellular lifeforms, and that such genes could serve as potential for further evolution.

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 [9,20]. Other reports show that genes required by more highly evolved species may reside without evident function in the genomes of prokaryotes [5] or viruses [33]. One cannot help, but notice that these findings corroborate the concept of cosmic bacteria and cosmic genes.

Unequivocal proof

A direct way to test the theory of cometary panspermia is 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 examine the samples for extraterrestrial microorganisms. With a daily input of cometary debris averaging some 100 ton, the possibility of detecting infalling microbes must surely exist.

The earliest experiments to search the upper atmosphere for microorganisms were carried out using high altitude balloons in the early to mid-1960s. Although microbiological techniques available at the time were 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 [4]. Positive detection of microorganisms at 39 km and a population density that increased with height pointed to a possible extraterrestrial source.

The sample return 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 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 possibility 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.

The stratospheric collection experiments of the 1960s have also been resumed by the Indian Space Research Organisation (ISRO) in collaboration with groups at Cardiff and Sheffield. The aim was to collect stratospheric air aseptically, and to examine it in the laboratory for signs of life. The sample collection was done using a number of specially manufactured sterilized stainless steel cylinders that were evacuated to almost zero pressures and fitted with valves that could be open and shut at different heights in the atmosphere. An assembly of such cylinders was suspended in a

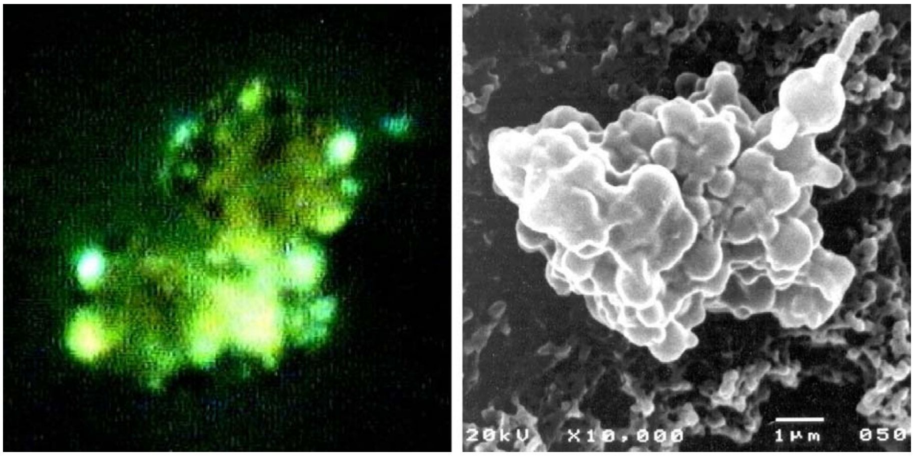

Fig. 6. Left: Clump of viable bacteria fluorescing in cyanine dye. Right: Scanning electron microscope picture of similar structure showing clump of cocci and a rod.

liquid Ne environment to keep them at cryogenic temperatures, and the entire payload launched from the TATA Institute Balloon launching facility in Hyderabad, India on 20 January, 2001. As the valves of the cylinders are opened upon ground telecommand at predetermined heights, ambient air rushes in to fill the vacuum, building up high pressures within the cylinders. The valves are shut after a prescribed length of time, the cylinders hermetically sealed and parachuted back to the ground.

Back on the ground the cylinders were carefully opened and the collected air made to flow through sterile membrane filters in a contaminant free environment. Any bacteria or clumps of bacteria present in the stratosphere would then be collected on these filters.

In the first phase of this investigation unambiguous evidence for the presence of clumps of viable cells were discovered in air samples collected from as high as 41 km, well above the local tropopause (16 km), above which no aerosols from lower down would normally be transported. The detection was made using a fluorescent dyes which are only taken up by the membranes of living cells. When the isolate treated with the dye is examined under an epifluourescence microscope the picture on the left of Fig. 6 is obtained. The picture on the right is an image from an electron microscope which shows a similar structure comprised of cocci and rods. The variation with height of the distribution of such cells indicates strongly that the clumps of bacterial cells are falling from space. Dr. Milton Wainwright of the University of Sheffield was further able to isolate and culture two organisms: one micrococcus and one microfungus closely related to known species which must therefore have fallen from the skies. The daily input of such biological material is provisionally estimated to be in the range one-third to one tonne over the entire planet.

If these findings are confirmed it would be difficult to maintain that such an input has no effect on terrestrial biology. On the contrary the biological and even perhaps medical implications are likely to be profound. The Universe would then have been shown to the grandest crucible of cryobiology.

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