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PANSPERMIA: EVIDENCE FROM ASTRONOMY TO METEORITES

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The theory of cometary panspermia is reviewed in relation to evidence from astronomy, biology and recent studies of meteorites. The spectroscopic signatures in interstellar material within our galaxy and in external galaxies that have been known for many years most plausibly represent evidence for the detritus of life existing on a cosmic scale. Such spectral features discovered in galaxies of high redshift points to life arising at a very early stage in the history of the Universe. Evidence of fossils of microscopic life forms in meteorites that have been discussed over several decades, and augmented recently with new data, reaffirms the case for cometary panspermia.

Keywords: Panspermia; interstellar dust; comets; meteorites.

1. Introduction

Aristarchus of Samos (310–230 BC) first introduced the idea of panspermia (seeds everywhere) into Western Philosophy as a response to the older Aristotelian doctrine of spontaneous generation. Despite the cogency of Aristarchus' arguments for panspermia, the rival theory of spontaneous generation remained overwhelmingly the dominant point of view well into the 19th century. Pasteur's classic experiments on the processes of fermentation in the mid-19th century demonstrated that microbial life appears always to be derived from pre-existing microbial life,[1] and it was declared accordingly that "spontaneous generation was finally dead".

The demise of the old doctrine of spontaneous generation led to the transfer of interest to panspermia as a mode of origin for terrestrial life. In 1861, Lord Kelvin in his presidential address to the British Association stated thus:

> "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 meteoritic 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 being covered with vegetation."

Two decades later, the concept of panspermia was given a more rigorous technical expression by Nobel Laureate Svante Arrhenius, first in a short paper in 1903 and later in his 1908 book "Worlds in the Making".[2,3] Long before the discovery of extremophilic bacteria, Svante Arrhenius had inferred that such survival properties must exist from experiments he conducted himself on taking seeds down to near 0 K. Arrhenius also calculated correctly the effect of radiation pressure of starlight on spores and argued that such living particles can be propelled quite naturally from one star system to another by this means. In this way, he introduced the concept of interstellar panspermia. Seven decades later Fred Hoyle and one of the present authors (NCW) extended the same idea and propounded the theory of cometary panspermia.[4]

Opposition to Arrhenius' formulation of panspermia was swift, and came from biologists who were at the time reformulating the old theory of spontaneous generation in a new form as the "primordial soup theory". In 1924, Becquerel[5] argued that bacteria would be inactivated and destroyed by the action of ultraviolet radiation, and this was used as a one-line disproof of panspermia. Although, Becquerel's intervention had the desired effect in diverting attention from panspermia, his objection turned out to be wrong. A clump of bacteria surrounded with biofilm would inevitably develop a thin outer skin of carbonized material that would provide nearly complete protection from ultraviolet light.[6]

Becquerel and other critics in the 1920s were also unaware of the extreme levels of ultraviolet resistance actually possessed by some species of bacteria. For instance, *Deinococus radiodurans* can withstand extraordinarily high doses of ultraviolet as well as ionizing radiation. Their resistance to such radiation is so high that Pavlov *et al.*[7] even suggested that *D. radiodurans* may have originated on Mars and been transported to Earth via a meteorite. Recently, it has been shown that other bacteria can also survive exposure to the harsh conditions of space. *M. radiodurans* and *B. subtlis* are two examples of microorganisms that were actually exposed for several months to the high vacuum and high radiation environments of space, and shown to survive.

It should be pointed out in this context that even inactivated bacteria with genomes that are damaged or inactivated can still carry the message of life from one cosmic location to another.[8] What remains beyond any dispute is that microbiological research over the past 20 years into extremophiles have provided ample evidence that Becquerel's strident claims in the 1920s denouncing panspermia were wrong.

In the primordial soup theory[9,10] that has become the dominant paradigm, an initially sterile Earth acquires life from material on our planet itself by processes that are localized here. This theory has recently been adapted to take account of biochemical inputs from comets and meteorites, inputs that may even include complex organic molecules such as dipeptides.[11,12] However, the process of starting primitive life, and thereby initiating neo-Darwinian evolution remains firmly Earth-bound in all the modern variants of the primordial soup theory.

2. Cometary Panspermia

The only secure empirical fact relating to the origin of life is encapsulated in the dictum enunciated by Louis Pasteur[1] — *Omne vivum e vivo* — all life from antecedent life. This is in fact the *raison d'être* for panspermia. If life is always derived from antecedent life in a causal chain, as is clearly manifest in present day life and throughout the fossil record, the question naturally arises as to when and where this connection ceased. The continuation of the life-from-life chain to a time before the first life appears on our planet and before the Earth itself formed implies the operation of "panspermia".[4,13,14] According to the theory of cometary panspermia comets provide the main amplification sites for microorganisms and also serve as vehicles for their transport throughout the universe.

In an alternative version of panspermia, Crick and Orgel[15] have suggested the idea of directed panspermia, which transfers the problem of origin to an extraterrestrial site, possibly invoking intelligent intervention. Fred Hoyle and one of the present authors have attempted to expand both the spatial and temporal domains in which cosmic abiogenesis may have occurred, focussing first on the totality of comets in our galaxy, and later on more extended cosmological settings.[14]

The prevalent view that all extraterrestrial organics arise abiotically has no secure empirical basis and is likely to be flawed. On the Earth, it is clear that life processes account for almost all the organic molecules on the planet. If biology is widespread on a cosmic scale, the detritus of living cells would also be expected to be widely distributed in the cosmos. The bulk of the organic molecules in space that was discovered from the 1970s would then be explained as break-up products of life-molecules.[16] Inorganic processes can scarcely be expected to compete with biology in the ability to synthesize systems of biochemicals resembling the detritus of biology, and accounting for as much as a third of all the carbon in the cosmos. So, wherever complex organics are found in an astronomical setting, one might legitimately infer that biology has been responsible for its spread.[16,17]

3. Modern Developments on Earth-Bound Abiogenesis

It is generally conceded that the path from chemicals to self-replicating biology must progress through a sequence of organizational steps of ever-increasing complexity. The most popular contender for one possible early step is the RNA world. Here nucleotides polymerize into random RNA molecules that lead to autonomously self-replicating macromolecules (ribozymes) without the need for an intermediary enzyme.[20] Likewise, other contenders of prebiotic development include the "Iron-sulphur world"[21] the "PNA (peptide nucleic acid) world"[22] and the "Clay World",[24] the latter involving an inorganic clay system serving as a primitive informational template. In view of the high abundance of silicon in the galaxy the clay world model might well have a special role to play in a cosmic context. The transition from any of these intermediate systems to a protogene system possessing prescriptive information for evolution, and finally to DNA-protein-based cellular life is still in the realm of speculation or hypothesis.[23,30]

The difficulty of finding unequivocal evidence of the relics of prebiology in the geological record has been a handicap for Earth-based theories of the origin of life. The suite of organics present in interstellar clouds[16] consistently directs us to possible origins away from Earth to more and more distant parts of the Universe. At the very least, the organic molecules needed for life's origins are much more likely to have been generated in a cosmic context rather than being formed *in situ* on Earth. Moreover, it is now becoming clear that life arose on Earth almost at the very first moment that it could have survived. During the period from about 4.3–3.8 Gy ago (the Hadean Epoch) the Earth suffered an episode of heavy bombardment by comets and asteroids.[25] Rocks dating back to the tail end of this epoch reveal evidence of an excess of the lighter isotope ^{12}C compared with ^{13}C pointing to the action of microorganisms that preferentially take up the lighter isotope from the environment.[26,27]

The success of the Miller–Urey experiments in the 1950s in synthesizing the monomers of biology from mixtures of inorganic gases led to the conviction that it was only a matter of time before the next steps from biochemical monomers to life could be demonstrated in the laboratory. Despite over half a century of effort, this goal has proved stubbornly elusive.[28,29] If one accepts the Hoyle–Wickramasinghe calculations[13] showing grotesquely small *a priori* probabilities for the transition of non-life to life, it would appear that only two options remain open. The origin of life on Earth was an extremely improbable event that occurred, but will effectively not be reproduced elsewhere. Or, a very much bigger system than was available on Earth, and a longer timescale was involved in an initial origination event, after which life was somehow transferred to Earth. How big or old that system needs to be is still a matter for debate. Arguments by Abel and Trevors[30] and Abel[23] suggest that within the framework of Big-Bang type cosmologies naturalistic protogene formation still faces almost insuperable difficulties. However, by whatever process life has emerged, this event of origination must be reckoned to be unique, and the subsequent spread of life throughout the universe more or less assured by the processes of "panspermia".[13,14,31,32]

4. Astronomical Model: Comets

The basic molecules that may be required for prebiotic chemistry − including H_2O, simple organics and PAHs are present in vast quantity in the Galaxy. All that one could hope to achieve in the way of further progress towards biochemistry in interstellar clouds is the production of moderately more complex organic molecules through gas-phase or grain-surface chemistry. These more complex organic molecules must then enter a watery medium in suitably high concentrations to begin the presumptive prebiotic chemistry that may have eventually led to life.

In the formation of a planetary system such as the solar system the first solid objects to form are the comets. These icy objects would have mopped up the molecules and dust of the parent interstellar cloud, and for a few million years after they condensed would have possessed liquid water interiors, due to the heating effect of radioactive decays. If even the minutest amount of microbial life was already present in the parent interstellar cloud, the newly-formed comets could serve to vastly amplify life on a very short timescale.

Prior to life being generated anywhere in the galaxy, primordial comets heated by decay of radioactive nuclides such as ^{26}Al and ^{60}Fe would have provided trillions of "warm little ponds" replete with water, organics and nutrients. Their huge numbers would have diminished vastly the improbability hurdle for life to originate. Recent studies of comet Tempel 1 have shown evidence of organic molecules including PAHs, clay particles as well as liquid water, providing an ideal setting for the operation of the "clay theory" of the origin of life.[24,34]

It has been argued that a single primordial comet of this kind will be favored over all the shallow ponds and edges of oceans on Earth by a factor 10^4, taking into account the total clay surface area for catalytic reactions as well as the timescale of persistence in each scenario.[34] With 10^{11} comets, the factor favoring solar-system comets over the totality of terrestrial "warm little ponds" weighs in at a figure of 10^{15} and with 10^9 sun-like stars replete with comets in the entire galaxy, we arrive at a factor of 10^{24} in favor of a cometary origin of life.

The next step in the argument is that once life got started in some comet somewhere, its spread in the cosmos becomes inevitable. The comets themselves are the amplifiers and distributers of life in the Galaxy. Dormant microorganisms are released in the dust tails of comets and propelled by the pressure of starlight to reach interstellar clouds. When a planetary system forms, the newly formed comets in that system provide sites for the amplification of surviving microorganisms that are incorporated in the new system.

Transport of microorganisms and spores within the frozen interiors of comets carries only a negligible risk of destruction, but transport in either naked form, within clumps of dust or within meteorites entails varying degrees of risk of inactivation by cosmic rays and UV light. However, the successful seeding of life requires only the minutest survival fraction between successive amplification sites. Of the bacterial particles included in every nascent cometary cloud only one in 10^{24} needs to remain viable to ensure a positive feedback loop for panspermia. All the indications are that this is a very modest requirement that is hard, if not impossible, to violate.

Whilst comets could supply a source of primitive life (archeae and bacteria) to interstellar clouds and thence to new planetary systems, the genetic products of evolved life could also be disseminated on a galaxy-wide scale.[25] Our present-day solar system which is surrounded by an extended halo of some 100 billion comets (the Oort Cloud) moves around the center of the galaxy with a period of 240 My. Every 40 million years, on the average, the comet cloud becomes perturbed due to the close passage of a massive molecular cloud. Gravitational interaction leads to hundreds of comets from the Oort Cloud being injected into the inner planetary system on each occasion, some to collide with the Earth. Such collisions cannot only cause extinctions of species (as one impact surely did 65 million years ago, killing the dinosaurs), but they could also result in the expulsion of surface material back into space.

A fraction of the Earth-debris so expelled survives shock-heating and could be laden with viable microbial ecologies, including diatoms as well as genes of evolved life. Such life-bearing Earth material could reach newly forming planetary systems in the passing molecular cloud within a million years of each ejection event. A new planetary system thus comes to be infected with terrestrial microbes and terrestrial genes that can contribute, *via* horizontal gene transfer, to an ongoing process of local biological evolution elsewhere.

5. Cosmological Options

How many events of origination of life has there been in the 13.8 Byr history of the Universe? Can life spread from a single origin in one galaxy to infect the entire universe? Such a spread is easiest when the Universe is much more compact than it is now, as in a model recently proposed by Gibson and Schild.[36] In this non-conformist HGD (Hydro Gravitational Dynamics) cosmology, the formation of Earth-mass clouds occur at the plasma-recombination stage 300,000 years after the Big Bang. These cloud fragments then condense into frozen H-rich planets which are later polluted with heavy elements from the first generation of supernovae. Gibson, Schild and Wickramasinghe[32] have shown that Earth-mass planets with iron cores, overlain with oceans rich in organic materials and weighed down with extensive H-He atmospheres, provide optimal conditions for a first origin of life. The ocean temperature is close to 647 K, the critical temperature of water, and organic synthesis under these ultra-high pressure, high temperature conditions is greatly speeded up. The volume of a typical such ocean on a primordial planet is $\sim 10^{10}$ km^3, and with 10^{80} such planets a gigantic cosmological "soup" with a total volume of 10^{90} km^3 is available for the origin of life. The primordial planetary bodies at this stage are separated by only some tens of AU and with collisional connections established between them, one could imagine a gigantic connected primordial soup in action. These optimal conditions would prevail for 10 million years, and cannot be remotely reproduced at any later cosmological epoch.

For judging efficiency in accomplishing an origin of life, the comparison to be made is between the volume of 10^{90} km^3 for the total set of primordial planets and $\sim$ 1–10 km^3 for all the hydrothermal vents in the Earth's oceans. A factor of nearly 10^{90} in probability is thus gained, compared with the factor of 10^{24} we found earlier in going from Earth to all the comets in the galaxy. The creation of life at one locality in this extremely dense, collision-dominated system in the early universe would lead to the fertilization of other habitats, and the spread life across the entire primordial universe within a few million years. After some 10 million years, however, ocean temperatures drop with the general cooling down of the Universe, and the primordial planets laden with microbes will freeze. The cosmological legacy of life will thereafter be carried within these frozen primordial planets, which Gibson and Schild identify as the baryonic dark matter of the Universe. Mergers and disruptions of such life-laden "giant comets" are associated with every event of star or planet formation occurring in the disk of the galaxy.

6. Interstellar Dust, PAH and Biological Molecules

Identifying the composition of interstellar dust in clouds has been a high priority for astronomical research since the early 1930s.[37] The dust absorbs and scatters starlight causing extinction of the light from stars, and re-emits the absorbed radiation in the infrared. An important clue relating to dust composition follows from studies of extinction of starlight. The total amount of the dust has to be as large as it can be if nearly all the available carbon and oxygen is condensed into grains.[37] The paradigm in the 1960s that the dust was largely comprised of water-ice was quickly overturned after the advent of infrared observations showing absorptions due to CH, OH, C-O-C linkages consistent with organic polymers (Ref. 38). The best agreement for a range of astronomical spectra embracing a wide optical wavelength interval turned out to be material that is indistinguishable from freeze-dried bacteria and the best overall agreement over the entire profile of interstellar extinction from the infrared to the ultraviolet was a mixture of desiccated bacteria, nanobacteria, including biologically derived aromatic molecules as seen in Fig. 1.

The distribution of unidentified infrared bands (UIBs) between 3.3 μm and 22 μm is almost identical in their wavelengths in very different emission sources, more or less irrespective of the ambient conditions. Figure 2 shows the spectrum of the planetary nebula NGC 7027 with arrows pointing to the strong absorption bands in the aromatic mixture used in Fig. 1.

Whilst PAHs (Polyaromatic Hydrocarbons), presumed to form inorganically, are the favored model for the UIBs, no really satisfactory agreement with available astronomical data has thus far been shown possible for abiotic PAHs.[38] This is a particularly serious problem if we require the set of UIB emitters and the 2175 A absorbers to be one and the same. The latter requirement is necessary because it is the starlight energy absorbed in the ultraviolet band that is being re-emitted as UIBs in the infrared.

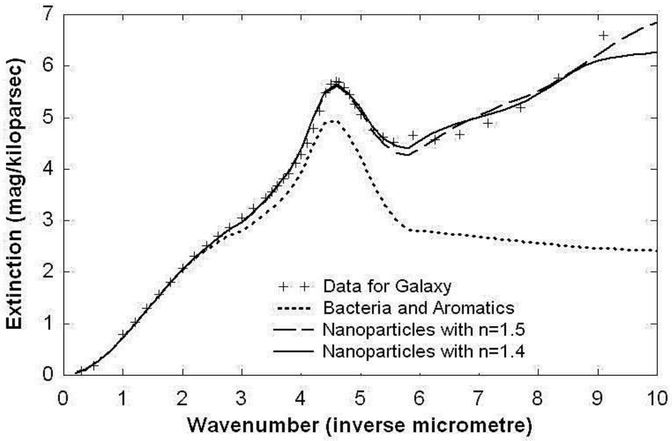

Fig. 1. Agreement between interstellar extinction (+) and biological models. Mixtures of hollow bacterial grains, 115 biological aromatic molecules and nanobacteria provide excellent fits to the astronomical data (Ref. 25).

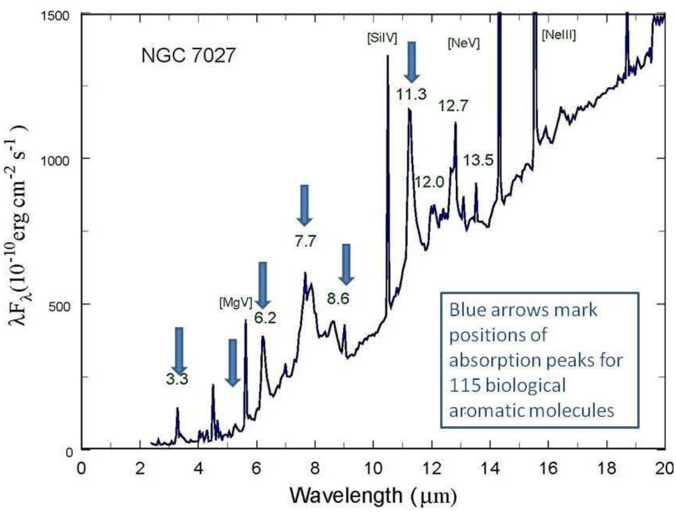

Fig. 2. IR spectrum of planetary nebula NCG7027 compared with main absorptions of 115 biological aromatic molecules.

Amongst the most distant galaxies displaying aromatic/biomolecular infrared signatures is a high red-shift infrared luminous galaxy at redshift $z = 2.69$, the spectrum of which is shown in Fig. 3 (Tepletz *et al.*[39]). This galaxy emitted its light when the Universe was at the tender age of 2 billion years according to standard Big Bang cosmology.

The idea that the material causing these emissions represents the degradation products of biology, as we have originally suggested, can be challenged only on

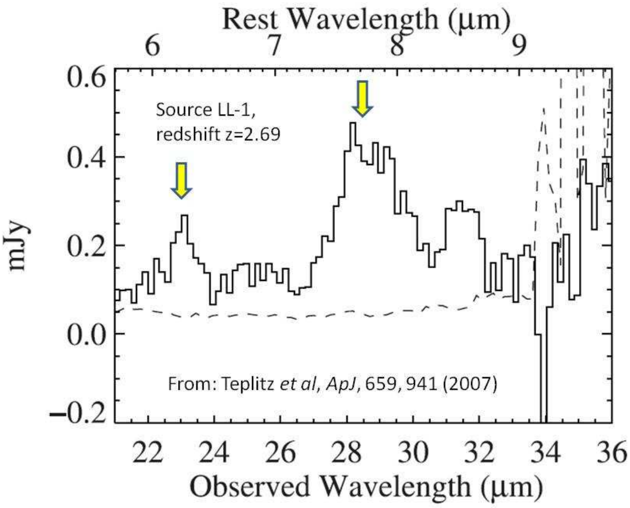

Fig. 3. Redshifted 6.2, 8.7, 11.3 micron bands in the source.[39]

the ground that extraterrestrial life is an "extraordinary hypothesis" requiring "extraordinary evidence" to support it. Yet very similar PAH-type organic molecules, ubiquitous in the terrestrial environment all have an undisputed origin in biology. The confinement of life to the Earth is indeed the most extraordinary hypothesis, and far less justifiable since mechanisms of viable transfer of microbes across the galaxy have been clearly identified.

Evidence of PAH-type biodegradation products also shows up in the form of a[25] 2175A spectral signature in recent observations of the most distant galaxies up to redshifts of at least 2.45. We thus have clear evidence that biologically related materials were formed within 2.5 billion years of the presumed Big-Bang origin of the universe.[40,41] The UV spectral feature for two intermediate redshift galaxies is shown in Fig. 4 compared with our calculated absorption profile for the biological aromatic ensemble that gives agreements with the IR and the mid UV absorptions in our galaxy.

Biological molecules would be expected to be present much earlier in the history of the universe. Dust extinction has been found in even more distant galaxies, and a high concentration of the life-element carbon has also been detected in the most distant radio galaxy at a redshift of $z = 5.19$ (Ref. 42). If the existence of life is judged by carbon abundance, it is possible to infer that "signs of life" show up within a billion years after the Big Bang — ready for cometary panspermia to take over as the universe continues to expand.

7. Comets and Biomaterial

There is growing evidence that the composition of dust in comets is very similar to that of interstellar dust. Since the exploration of comet Halley in 1986, the infrared

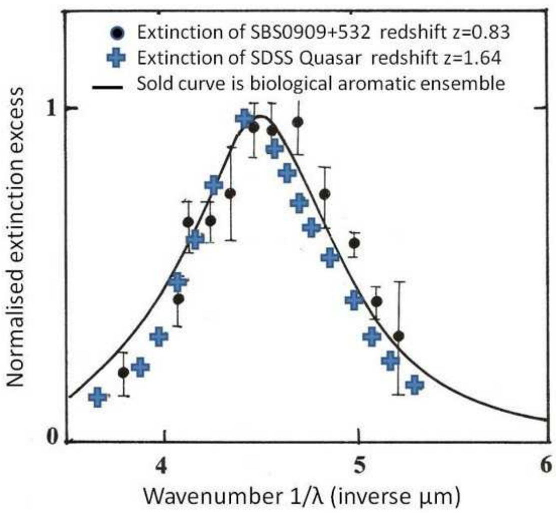

Fig. 4. The 2175A feature in two high redshift galaxies, compared with aromatic biomolecules.[40,41]

spectra of cometary dust have been found to be consistent with an organic-biological grain model.

Spectral features near 19, 24, 28 and 34 μm observed by ISO (Infrared Space Observatory) have been attributed to hydrated silicates in several protoplanetary disks, and in comet Hale–Bopp.[42,43] The uniqueness of some of these assignments is still in doubt, but even on the basis of a silicate identification of the principal infrared bands, it can be shown that such material can make up only some few percent of the mass of the dust, the rest being largely organic.[37] This appears to be the case for the infrared flux curve of comet Hale–Bopp, obtained by Crovisier *et al.*[43] when the comet was at a heliocentric distance of 2.9 AU.

The dashed curve in Fig. 5 shows the behavior of a mixed culture of microorganisms containing about 20% by mass in the form of diatoms. Olivine dust, which has a much higher mass absorption coefficient within its absorption bands than biomaterial, makes up only 10% of the total mass in this model.[25]

8. Capture of Comet Dust in the Stratosphere

In the Stardust mission to comet Wild2 cometary particles were collected at high impact speeds onto blocks of aerogel. Survival of fragile organic structures (e.g., bacteria) would have been virtually impossible under such conditions, and this was borne out in the results.

An obvious place to find fragile particles from comets is the Earth's upper atmosphere. Cometary meteoroids and dust particles are known to enter the atmosphere at a more or less steady rate, averaging $\sim 10^2$ tonne/day. Although, much of the incoming material burns up as meteors, a significant fraction survives entry. Organic

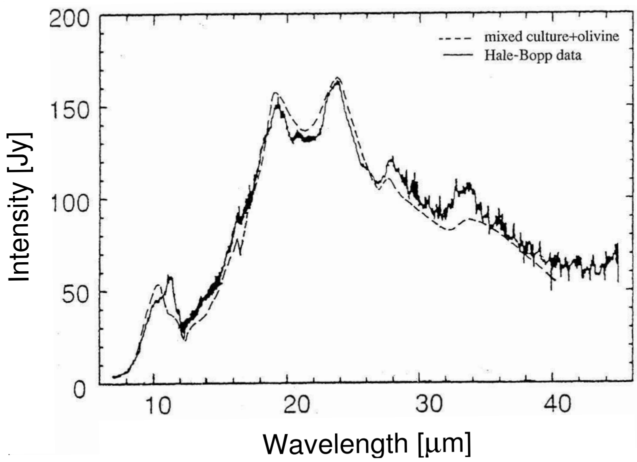

Fig. 5. The infrared spectrum of comet Hale–Bopp obtained by Crovisier *et al.*[43] when the comet was at a heliocentric distance of 2.9 AU (jagged curve). The dashed curve is for a mixed culture of microorganisms and olivine dust which comprised 10% of the total mass. The diatoms (diatomaceous silica) make up 20% by mass.

grains of micron sizes, arriving as clumps and dispersing in the high stratosphere, would be slowed down gently and would not be destructively heated. The Earth's atmosphere could thus serve as an ideal collector of organic cometary dust.

Techniques for stratospheric collection of cometary dust must, of necessity, involve procedures for either sifting out terrestrial contamination or for excluding contamination altogether. Such stratospheric dust collections have been carried out from as early as the mid-1960s.[45] Balloons and rockets reaching heights well above 50 km were deployed which consistently brought back algae, bacteria and bacterial spores. Although some of the microorganisms thus collected were claimed to exhibit unusual properties, such as pigmentation and radiation resistance, their possible extraterrestrial origin remained in serious doubt. No DNA sequencing procedure was available at the time to ascertain any significant deviations there might have been from related terrestrial species. Moreover, both the collection and laboratory techniques in the 1960s left open a high chance of contamination.

In 2001, the Indian Space Research Organisation (ISRO) launched a balloon into the stratosphere carrying devices to collect stratospheric air under aseptic conditions.[46] The procedure involved the use of cryogenically cooled stainless steel cylinders which were evacuated and fitted with valves that could be opened when they reached a predetermined altitude. Large quantities of stratospheric air at 41 km were thus collected and the cylinders were brought back for analysis.

The ultra-high pressure stratospheric air contained within the cylinders was carefully released and passed through a system including millipore membrane filters. Upon such filters stratospheric aerosols were collected, extreme care being taken at every stage to avoid contamination. The particles that were collected fell into two

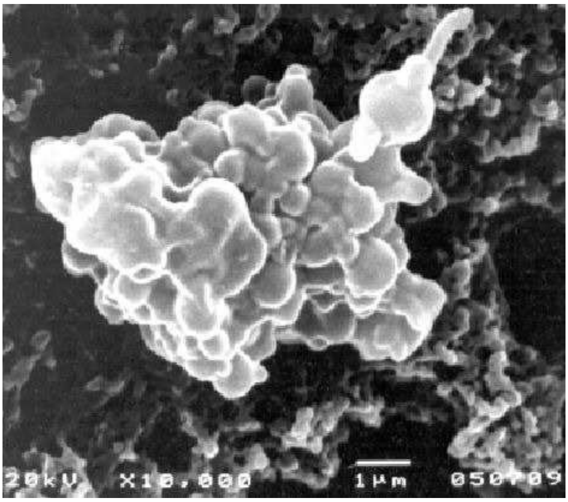

Fig. 6. A carbonaceous stratospheric particle from 41 km resembling a clump of cocci and a rod bacterium.

broad classes: (a) mineral grain aggregates, very similar to Brownlee particles, but somewhat smaller; (b) fluffy carbonaceous aggregates resembling clumps of bacteria (see Fig. 6). Typical dimensions were about 10 μm.

The cometary origin of such particles is very strongly indicated, the altitude of 41 km being too high for lofting 10 μm sized clumps of solid material from the Earth's surface. In addition to structures such as those shown in Fig. 6, which can be tentatively identified with degraded bacteria, the stratospheric samples also revealed evidence of similar sized bacterial clumps that could not be cultured, but were nevertheless detected by the use of a fluorescent dye (carbocyanine dye). The uptake of the dye revealed the presence of living cells in the clumps.

In a separate series of experiments a few microbial species were cultured from the same stratospheric air samples by Wainwright *et al.*[47] and there is tentative evidence that these may also have come from comets. A later balloon flight in 2008 collected more stratospheric material and analysis by Shivaji *et al.*[48] yielded cultures of three hitherto unknown microbial species which were highly resistant to ultraviolet light. One of the new species was named *Janibacter hoylei*, in honor of Fred Hoyle.

9. Microfossils in Meteorites

The topic of microfossils in carbonaceous chondrites has sparked bitter controversy ever since it was first introduced in the mid-1960s by Claus *et al.*[49] Since carbonaceous chondrites are generally believed to be derived from comets, the discovery of fossilized life forms in comets would provide strong *prima facie* evidence in support of the theory of life in comets and cometary panspermia. However, some contami-

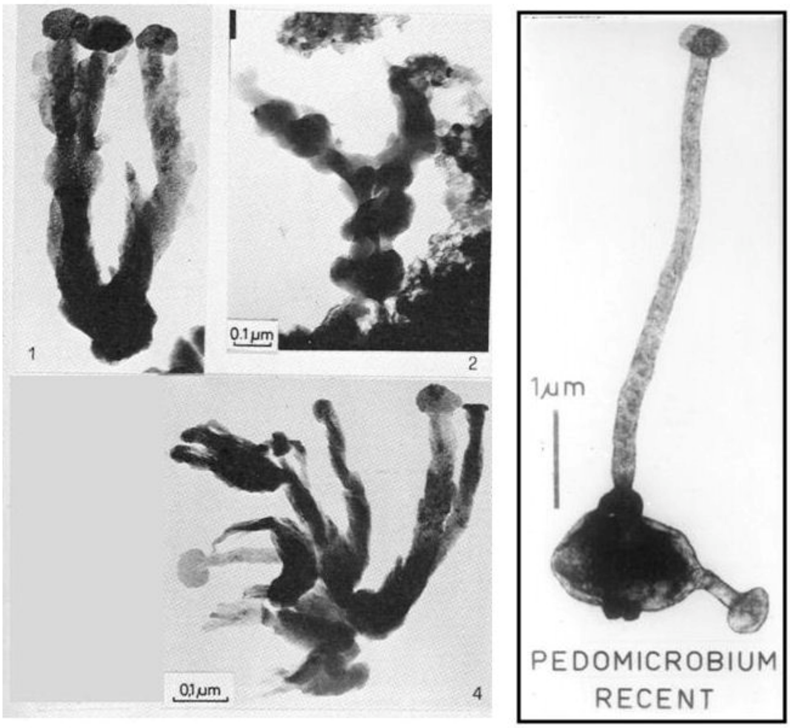

Fig. 7. Microfossils in the Murchison meteorite discovered by Pflug[50] (Left). On the right-hand frame is a modern bacterium — *pedomicrobium* — a matching morphology and species. Note that the structure within the meteorite is stunted by a factor of ~ 5 compared to the terrestrial specimen.

nation was discovered in the original samples, and claims that all micro structures (organized elements) discovered in meteorites were artifacts or contaminants led to a general rejection of meteoritic microfossil identifications in the 1960s.

The situation remained so until early in 1980 when H. D. Pflug found a similar profusion of "organized elements" in ultra-thin sections prepared from the Murchison meteorite, a carbonaceous chondrite that fell in Australia on 28 September 1969.[50] The contaminant-free experimental methods adopted by Pflug appeared to be beyond reproach. Thin sections of the meteorite were placed on membrane filters and hydrofluoric acid was used to dissolve-out the bulk of the minerals present and the residue examined in an electron microscope. Figure 7 shows an example of Pfug's findings. Not only were these morphologies strikingly characteristic of particular types of fossil microbes, but laser ion probe analysis yielded elemental and molecular compositions within these structures that were also consistent with life. These studies made it very difficult to reject the fossil identification. More recent work by Hoover[51] provided even more striking evidence of microbial fossils in the Murchison meteorite as shown in Fig. 8.

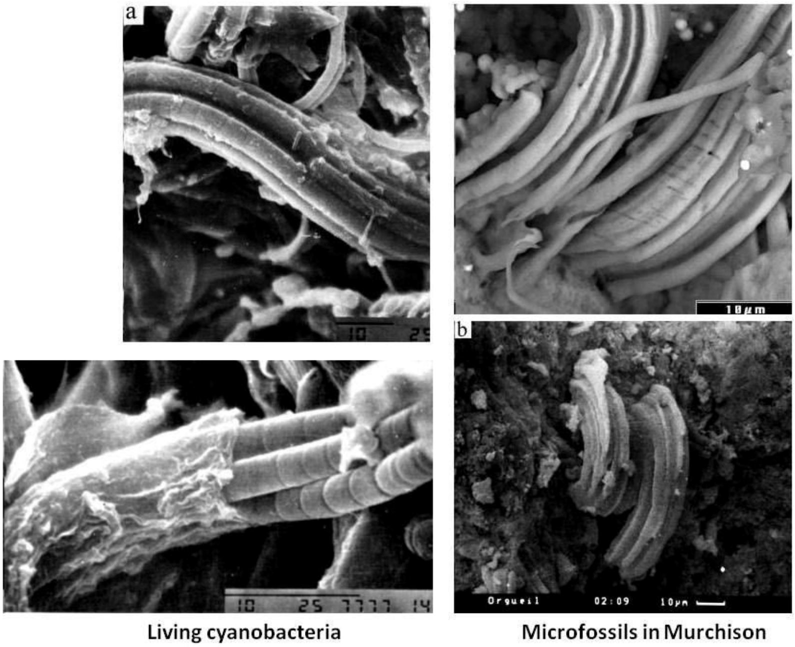

Fig. 8. Structures in the Murchison meteorite compared with living cyanobacteria.[50]

Just as in the case of the Copernican revolution of the 16th century correct ideas in science continue to reaffirm their validity, repeatedly and in diverse and unexpected ways. Ultimately a paradigm shift is forced into place. Resistance to the theory of cometary panspermia has been every bit as ferocious as was the opposition to the Copernican revolution in the 15th and 16th centuries. In 1981, Hoyle and one of us (NCW) were left in no doubt that H. D. Pflug's evidence of microbial life in meteorites constituted decisive proof of the existence of life in comets (Fig. 7).

Respondent's to this, and similar work, dismiss the "organized elements" as nonbiological and insist that morphology alone should not be used to classify the structures as biological. This assertion appears to overlook the elemental evidence mentioned earlier, as well as many other bio-markers that have been identified in carbonaceous meteorites. One such marker is the enantiomeric excesses of biological amino acids shown to be indigenous to CI1 meteorites through $^{13}C/^{12}C$ ratios. The presence of complex organics, excesses of biological stereo-isomers of amino acids and the striking morphologies in carbonaceous chondrites are all predicted by cometary panspermia. The search for further proof continues as opposition to panspermia persists on the unreasonable basis that existing evidence is either insufficient or the result of terrestrial contamination.

However, all this might conceivably change following the most remarkable discovery of what we consider to be fragments of a porous comet's crust that fell in the form of meteorites. Minutes after a fireball event was seen over the skies of

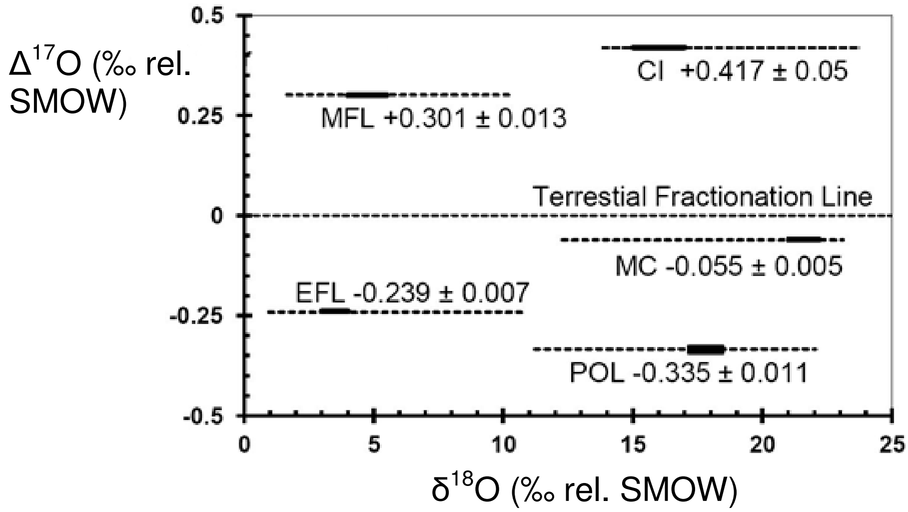

Fig. 9. Oxygen isotope $\Delta\ ^{17}$O (‰ rel. SMOW) values of a sample of the Polonnaruwa meteorite (POL) presented by Wallis *et al.*.[54] Data for MFL: martian fractionation from Franchi *et al.*, 1999. EFL: eucrite fractionation from Greenwood *et al.*, 2005. CI: fractionation line for CI1 chondrites and MC: fractionation of Meta-C chondrites (B-9704 and Y-86789) from Clayton *et al.*, 1998, cited in Ref. 54.

central Sri Lanka on 29 December 2012, a large meteoroid disintegrated and fell in a paddy field in the village of Aralaganwill, located a few miles away from the historic ancient city of Polonnaruwa. At the time of entry into the Earth's atmosphere the parent body of this Polonnaruwa meteorite would have had most of its interior porous volume filled with water, volatile organics and possibly a component of fossilised and viable living cells. Police reports of local people burning their hands when touching unusual stones in this area led to them contacting the Medical Research Institute in Colombo. A subsequent collection and investigations into the witnessed fall led to the recovery of many stones later shown to be meteorites with a cometary origin.[52–54]

A summary of the triple oxygen isotope analysis conducted by laser fluorination at the isotope laboratory at the University of Göttingen, Germany, presented by Wallis *et al.*,[54] is shown in Fig. 9 and highlights that the Polannaruwa meteorite displays a non-terrestrial isotopic signature.

Images of the sample at low magnification displayed a wide range of biological structures that were distributed and enmeshed within a fine-grained matrix, examples of which are shown in Figs. 10 and 11. They include fresh water and seawater diatoms and an extinct microbial fossil (Fig. 11(d)) known as an acritarch. Some of these structures are deeply ingrained in the rock matrix and the range of species we found cannot be reasonably explained on the basis of contamination. Any similarity to species of diatoms on Earth can also be explained by panspermia. It is a curious fact that diatoms appear very suddenly in the geological record some 180 million

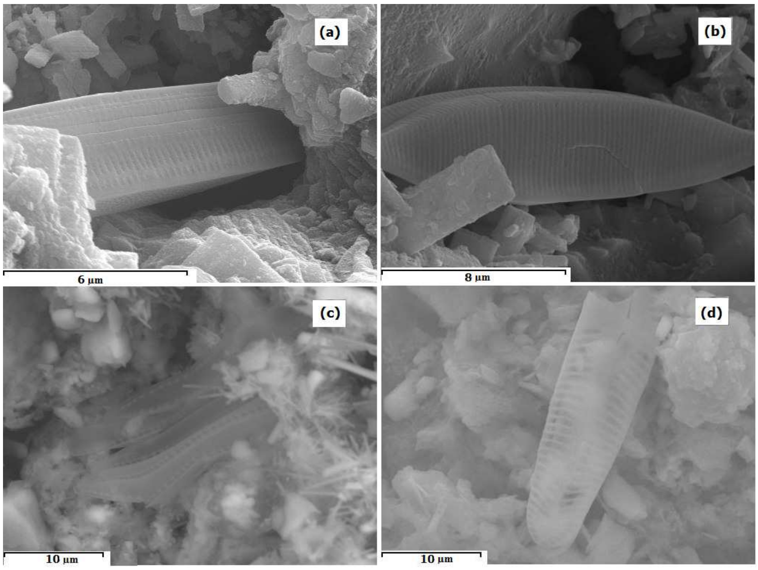

Fig. 10. Electron microscopy images of various diatoms found in the Polonnaruwa meteorite and presented by Wickramasinghe *et al.*[52,53] and Wallis *et al.*[54] The diatoms were present in both damaged (b) and (d) and undamaged (c) and (a) forms as well as some being clearly embedded in the rock matrix (b) and (c).

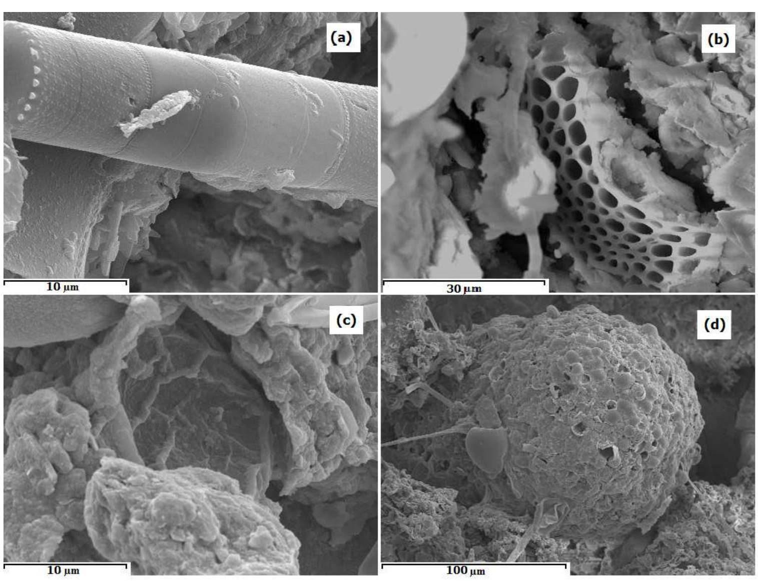

Fig. 11. Additional electron microscopy images of various biological entities found in the Polonnaruwa meteorite. Wickramasinghe *et al.*[52,53] and Wallis *et al.*[54] highlight the presence of marine diatoms (a) as well as ancient fossils (c) and (d) and carbonaceous, nitrogen deficient biological structures (b).

years ago. Considering the extreme stability of their silica shells, the absence of fossils in earlier epochs supports the idea of a cometary injection.

On the basis of the data summarized in Figs. 10, 11, we conclude that the identification of fossilized diatoms in the Polonnaruwa meteorite is established beyond much doubt. Since this meteorite is interpreted to be a cometary fragment, the idea of life in comets is supported by the new data. It is natural to expect that the data itself, as well as their interpretation, will come to be challenged for a while mostly on account of the long-held prejudice against the concept of panspermia. In the long term, however, facts must prevail over cultural prejudice and the universe will be the final arbiter.

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