Biodata of **Chandra Wickramasinghe**, author of "*Origin of Life and Panspermia*."

Chandra Wickramasinghe, Sri Lankan-born mathematician, astrophysicist, and astrobiologist, is one of the pioneers of the modern theories of panspermia. His early work on the organic composition of interstellar dust grains in the 1960s and 1970s has been amply vindicated by modern discoveries of PAHs and organics in the Universe. He did his Ph.D. at Cambridge University under the guidance of the late Sir Fred Hoyle (in 1963 and his Sc.D. in 1973) and has been a collaborator with Hoyle over nearly four decades. He was a Fellow of Jesus College Cambridge from 1962 to 1973 and thereafter Professor at Cardiff University where he set up the Cardiff Centre for Astrobiology in 1989. The recipient of several international honors and honorary degrees, he is a leading figure in modern astrobiology. He has authored or coauthored over 20 books and some 400 scientific papers, with over 70 of these in the journal *Nature*.

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ORIGIN OF LIFE AND PANSPERMIA

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1. Introduction

In the late 1920s, Oparin (1953) and Haldane (1929) introduced the 'Primordial Soup' theory of the origin of life, proposing that the atmosphere of the primitive Earth comprised of a reducing mixture of hydrogen, methane and ammonia and other compounds. Lightening and solar ultraviolet provided the energy to dissociate these molecules, and the radicals so formed recombined through a cascade of chemical reactions to yield biochemical monomers such as amino acids, nucleotide bases and sugars from which life was supposed to arise. In the 1950s, the classic experiments of Miller and Urey (1959) demonstrated the feasibility of the Oparin-Haldane chemistry, and this led to the belief that life could be generated de novo as soon as the biochemical monomers were in place. The formation of the first fully functioning, self-replicating life system with a potential for Darwinian evolution remains an elusive concept, however.

It is generally conceded that the path from chemicals to self-replicating biology must progress through a sequence of organisational steps of ever-increasing complexity. The most popular contender for one possible early step is the RNA world. Here nucleotides polymerise into random RNA molecules that lead to autonomously self-replicating macromolecules (ribozymes) without the need for an intermediary enzyme (Orgel and Crick, 1968). Likewise, other contenders of prebiotic development include the 'iron-sulphur world' (Wachtershauser, 1990), the 'PNA (peptide nucleic acid) world' (Bohler et al., 1995) and the 'clay world' (Cairns-Smith, 1966), 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 cybernetic information for evolution and finally to DNA-protein-based cellular life is still in the realm of speculation or hypothesis (Abel and Trevors, 2006).

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 (Kwok, 2009) 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 3.8 to 4.3 By ago (the Hadean Epoch), the Earth suffered an episode of heavy bombardment by comets and asteroids (Wickramasinghe et al., 2010). 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 (Manning et al., 2006).

The success of the Miller-Urey experiment 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. If one accepts the calculations showing grotesquely small a priori probabilities for the transition of non-life to life (Hoyle and Wickramasinghe, 1982), 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 were 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 (2006) and Abel (2009) 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 as unique and its subsequent spread of life throughout the universe assured by the processes of 'panspermia' (Hoyle and Wickramasinghe, 1980, 1981, 1982, 2000).

2. Panspermia

The only secure empirical fact relating to the origin of life is encapsulated in the dictum enunciated of Louis Pasteur – *Omne vivum ex vivo* – all life from antecedent life (Pasteur, 1857). If life is always derived from antecedent life in a causal chain, which is clearly manifest in present-day life and through the fossil record, the question naturally arises as to when and where this connection may have 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'.

The basic concept of panspermia has a history going back centuries – to the time of classical Greece and even before. It refers in general to the widespread dispersal of the 'seeds of life' in the cosmos (Hoyle and Wickramasinghe, 2000; Arrhenius, 1903, 1908). Whilst the Francis Crick and Leslie Orgel's idea of

directed panspermia transfers the problem of origin to another site, possibly invoking intelligent intervention (Crick and Orgel, 1973). Fred Hoyle and the writer have attempted to expand the spatial and temporal domains in which cosmic abiogenesis may have occurred, focussing in particular on totality of comets in our galaxy. Like Crick and Orgel (1973), we were influenced by the super-astronomical odds against the transition from organic molecules to even the most primitive living system – judged for instance by the highly specific complexity of the arrangements of molecules in DNA or enzymes.

The popular view that all extraterrestrial organics arise abiotically – that is to say through non-biologic processes – has no secure empirical basis and is likely to be flawed. On Earth, it is clear that life processes account for almost all the organic molecules on the planet. If biology can somehow be shown to be 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 would then be explained as break-up products of life molecules (Kwok, 2009). Inorganic processes can scarcely be expected to compete with biology in the ability to synthesise systems of biochemicals resembling the detritus of biology. So wherever complex organics are found in an astronomical setting, one might legitimately infer that biology has spread (Wickramasinghe, 2010). We shall return to this topic in Sect. 6.

3. Astronomical Options: 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 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 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 it 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 (Fig. 1) have shown evidence of organic molecules including PAHs, clay particles as well as liquid water,
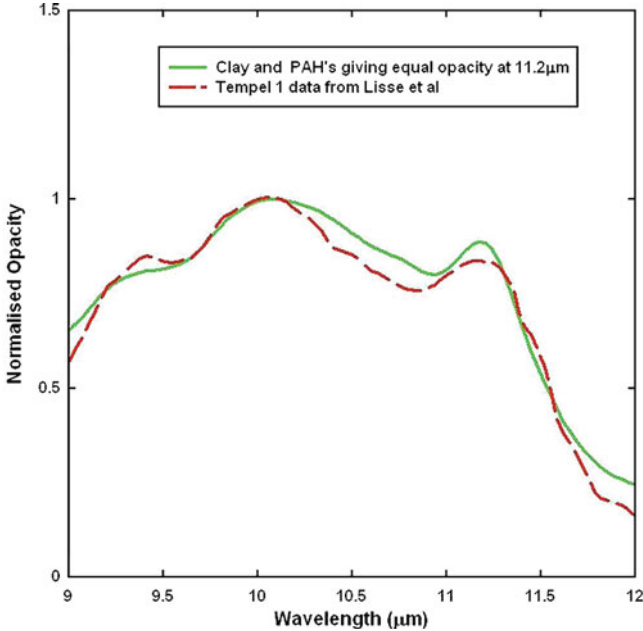
Figure 1. Normalised opacities near $\lambda = 10$ μm due to mixtures of clays and biological aromatic molecules (*solid curve*). Comparable contributions at $\lambda = 11.2$ μm from clays and aromatic molecules fit the data (*dashed curve*) best.

providing an ideal setting for the operation of the 'clay theory' of the origin of life (Wickramasinghe et al., 2009; Napier et al., 2007).

Together with Janaki Wickramasinghe and Bill Napier, the writer has argued that a single primordial comet of this kind will be favoured over all the shallow ponds and edges of oceans on Earth by a factor 10^4, taking into account the total clay surface area for catalytic reactions as well as the timescale of persistence in each scenario. With 10^{11} comets, the factor favouring solar system comets over the totality of terrestrial 'warm little ponds' weighs in at a figure of 10^{15}, and with 10^9 sun-like stars replete with comets in the entire galaxy, we tot up a factor of 10^{24} in favour of a cometary origin life.

The next step in the argument is that once life got started in some comet somewhere, its spread in the cosmos becomes inevitable. 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
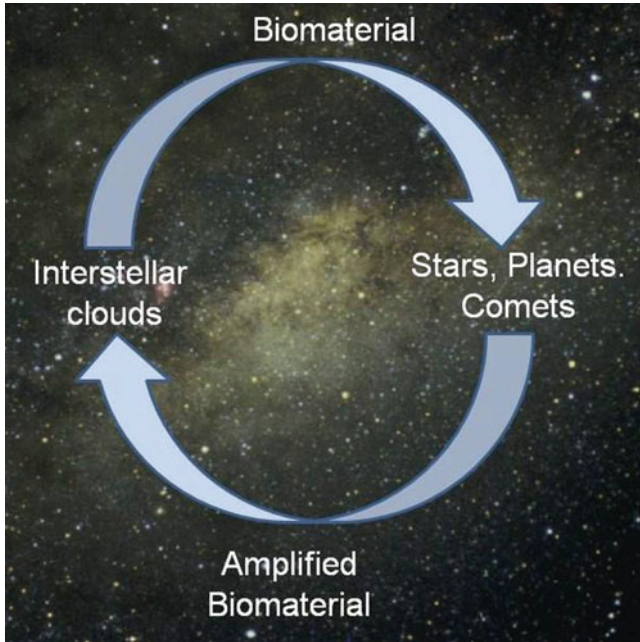
Figure 2. Feedback loop of cometary panspermia. Comets amplify and distribute microbial life at every star-/planet-forming event.

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. The feedback loop of cometary panspermia is shown schematically in Fig. 2. At the present time, this loop has been traversed some 10^{10} times, once for every sun-like star. 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 (archaea and bacteria) to interstellar clouds and thence to new planetary systems, the genetic products of evolved life could also be disseminated on a galaxy-wide scale (Wickramasinghe and Napier, 2008). Our present-day solar system which is surrounded by an extended halo of some 100 billion comets (the Oort cloud) moves around the centre of the galaxy with a period of 240 My. Every 40 million years, on the average, the comet cloud becomes perturbed due to the close passage of a molecular cloud. Gravitational interaction leads to hundreds of comets from the Oort cloud being injected into the inner planetary system, some to collide with the Earth. Such collisions can not only cause extinctions of species (as one impact surely did 65 million years ago, killing the dinosaurs), but they could also result in the expulsion of surface material back into space.

A mechanism thus exists for the genes of evolved Earth life to be transferred to alien planets. A fraction of the Earth debris so expelled survives shock heating and could be laden with viable microbial ecologies as well as genes of evolved life. Such life-bearing Earth material could reach newly forming planetary systems in the passing molecular cloud within a million years of the 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. Once life has got started and evolved on an alien planet or planets of the new system, the same process can be repeated (via comet collisions) transferring genetic material carrying local evolutionary 'experience' to other molecular clouds and other nascent planetary systems. If every life-bearing planet transfers genes in this way to more than one other planetary system (say 1.1 on the average) with a characteristic time of 40 My then the number of seeded planets after 9 billion years (lifetime of the galaxy) is $(1.1)^{9,000/40} \sim 2 \times 10^9$. Such a large number of 'infected' planets illustrates that Darwinian evolution, involving horizontal gene transfers, must operate not only on the Earth or within the confines of the solar system but on a truly galactic scale. Life throughout the galaxy on this picture would constitute a single connected biosphere.

4. Cosmological Options

How many events of origination of life has there been in the 13.7-By history of the Universe? Can life spread from a single origin in one galaxy to infect the entire universe?

Escape from a galaxy of life-bearing particles, bolides or comets is in principle possible. The value of the escape speed from a galaxy such as ours cannot be determined precisely, but it must surely exceed the orbital velocity of stars in the outer spiral arms, ~250 km/s. Assuming that particles can reach escape speed, say 1,000 km/s (dust could be accelerated by radiation pressure, comets and bolides by gravitational encounters), the distance traversed in the lifetime of our galaxy in $\sim 10^{10}$ years is ~10 Mpc. Diffusion of life over much greater distances will be severely limited by horizon constraints within an expanding universe. Thus, life from a single origin in one galaxy might be thought to be contained within a cluster of galaxies stretching over several Mpc but not beyond.

In standard ΛCDM Big Bang cosmologies, the problem will not be alleviated by going to an earlier epoch of the Universe. In such cosmological models, the first life and its panspermic dispersal can begin only after star formation gets under way and supernovae produce and disperse the heavy elements for life. This happened about 1.3 Gy after the Big Bang according to conformist cosmology, when the universe was about 15% of its present size, and intergalactic distances were also scaled down by the same factor. Transport times, survival constraints

and horizon restrictions will still inhibit full-scale cosmological panspermia from a single origin.

The only way to avoid a horizon-limited spread of life would be to adopt a non-conformist cosmological model such as that of Gibson and Schild (2009), which involves the creation of Earth-mass clouds at the plasma recombination stage 300,000 years after the Big Bang. In this model, these cloud fragments condense into frozen planets which are then polluted with heavy elements from the first generation of supernovae. Gibson, Schild and the present author 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 (Gibson et al., 2010). The volume of a typical such ocean on a primordial planet is ~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 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 ~1–10 km^3 for all the hydrothermal vents in the Earth's oceans. A factor of nearly of 10^{90} in probability is thus gained, compared with the factor of 10^{24} we found earlier in going from Earth to 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 fertilisation of other habitats and the spread of 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 (2009) 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 disc of the galaxy (Figs. 3 and 4).

To conclude this section, it should be stressed that there still remain unsolved problems concerning the origin of prescriptive information (protogene emergence) upon which all life depends. The cybernetic nature of life demands that the processes leading to its emergence be steered and regulated at every metabolic turn. Existing models of abiogenesis are incapable of accounting for such processes, even with the advantage of an enhancement of probability by the factor 10^{90} that was discussed above. Abiogenesis modellers still have a great deal of work to do before the ultimate origin of life by naturalistic processes can be fully understood.
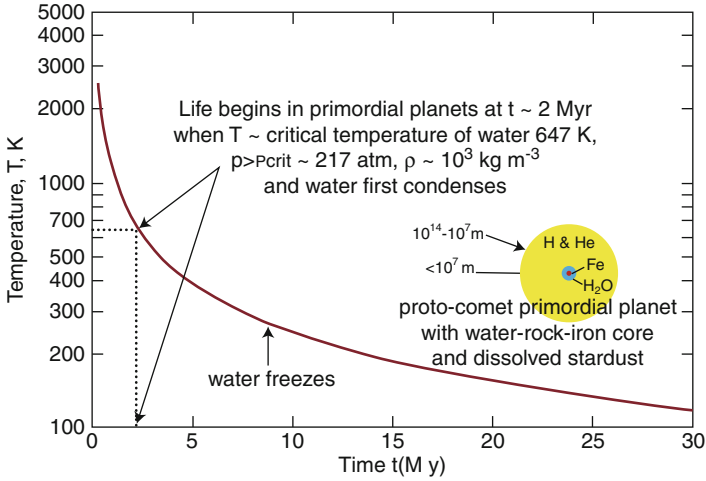
Figure 3. Temperature of the Universe as a function of time in million years after the Big Bang, showing stage at which life might optimally arise according to Gibson, Schild, Wickramasinghe model.
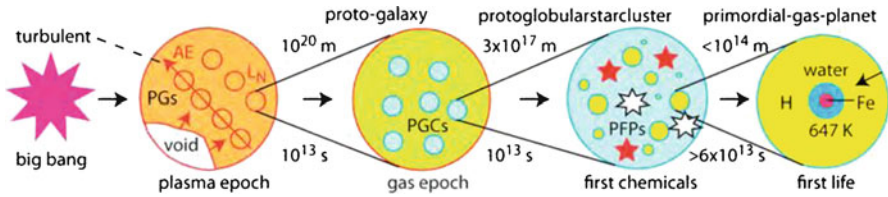
Figure 4. Sequence of steps showing the progression to warm primordial planets in which life originates. Courtesy: Carl Gibson.

5. Extremophiles and Survival of Cosmic Bacteria

The discovery of bacteria and archaea occupying the harshest environments on Earth provides indirect support for panspermia. Viable transfers of microbial life from one cosmic habitat to another require endurance of high and low temperatures as well as exposure to low fluxes of ionising radiation delivered over astronomical timescales. Survival at some level is needed if panspermia is to work. For microbes deep frozen within kilometre-sized frozen bodies, such as comets or planets, survival for unlimited cosmological timescales would be assured. Individual clumps of microorganisms and microbes embedded in small bolides will, however, have some limits to survivability, but even for naked clumps of microbes survival to some degree during interstellar/interplanetary transit is guaranteed.

A clump of bacteria surrounded with biofilm would inevitably develop a thin outer skin of carbonised material that would provide nearly complete protection

Table 1. Survival of spores of *B. subtilis*.

Mission	Duration of vacuum exposure (days)	Survival fraction at end of exposure (%)
Spacelab 1	10	70
EURECA	327	25
LDEF	2,107	1.4 ± 0.8

Data from Horneck (1993) and Horneck et al. (1995).

from ultraviolet light (Wickramasinghe and Wickramasinghe, 2008). Exposure to ionising radiation such as cosmic rays poses a more serious potential threat, however. The doses of ionising radiation that limit viability appear to be critically dependent on bacterial species. Table 1 shows the percentage of spores of *Bacillus subtilis* surviving after naked exposure to space vacuum in the solar vicinity (Mileikowsky et al., 2000).

Within the solar system, the radiation doses received by an outward-moving bacterium depend critically on the phase of solar activity, being highest at times near the peak of the solar cycle. The average radiation dose received at 1 AU over a timescale comparable to the 11-year period of the solar cycle is less than 10 Mrad, and so viability will not be expected to be drastically reduced. The LDEF experiment shows a reduction to 1% for the extreme case of an unprotected, unfrozen (at ∼1 AU) bacterial culture. Freeze-dried clumps of bacteria or bacterial spores are expected to fare significantly better. Far from a star, in a typical interstellar location, a very much lower flux of ionising radiation would be delivered over astronomical timescales, and the total dose delivered is likely to be less relevant than the incident flux.

The estimated doses of ionising radiation intercepted by bacterial clumps in an unshielded interstellar cloud and are in the range 5–15 Mrad in 10^5 years. Experiments done so far to determine viability as a function of total dose are most likely to be irrelevant for our purpose. Laboratory studies have invariably used very high fluxes of ionising radiation delivered in short pulses, at room temperature in the presence of air. Extrapolation from these studies to the astronomical case involves many uncertainties. In particular, most damage resulting from free-radical formation will be eliminated in an anaerobic environment, and low-flux long-time intervals may not equate to short pulses of high-flux radiation in the laboratory case.

Citing short pulse – high-flux experiments, Horneck et al. (2002) point out that for spores embedded in a meteorite, the timescale for survival to a 10^{-40}% level (due to primary and secondary CR effects) at a depth of 2–3 m is ∼25 My. The same surviving fraction is obtained for shielding at a depth of 1 m after 1 My, and for a naked spore the estimated timescale is ∼0.6 My. Over timescales of 3×0.6 My, the survival fraction is 10^{-18}. A clump of bacterial spores travelling at 10 km/s would traverse a distance of 18 pc during this time, comfortably less than the mean distance between cometary/planetary systems.

There are strong indications that the survival rates quoted above are an underestimate. They are based on experiments conducted at atmospheric pressure with normal levels of humidity (Lindahl, 1993). There is evidence that bacterial endospores are resistant to inactivation by free-radical damage and chemical processes because their cytoplasm is partially mineralised and their DNA is stabilised (Nicholson et al., 2000). Most significantly, it has been found that bacterial spores (genus Bacillus) in the guts of a bee preserved in amber for 25–40 My could be revitalised (Cano and Borucki, 1995). Similarly, bacterial spores in 250-My-old salt crystals have also been revitalised (Vreeland et al., 2000). In both these studies, the most stringent sterilisation techniques were used to avoid contamination of the samples, and the authors are confident that they have revived bacterial spores of great ages. With a natural background radioactivity (of rocks) of ~1 rad per year, we have here evidence of survival with doses of 25–250 Mrad of ionising radiation.

More recently, Bidle et al. (2007) have examined the most ancient terrestrial ice deposits in the Antarctic and found evidence of viable bacteria/bacterial genes in 8-My-old ice. They estimate an average half-life of bacteria under such conditions of ~1.1 My. The importance of these results in relation to panspermia cannot be denied. To avoid this conclusion, some scientists have used phylogenetic arguments. They point out that the revived organisms bear a close relationship to contemporary species, and so argue that they must be contaminants. However, panspermia theories permit re-introductions of the same organism (stored in comets) separated by millions of years, so no evolutionary divergence is required. Recent phylogenetic studies have indeed shown that 'horizontal' gene transfers across branches of Carl Woese's tree of life befuddle attempts to use the 'tree' as guiding principle or as an evolutionary clock (Woese and Fox, 1977). The phylogenetic modernity of the microorganisms found, as well as their survival over millions of years, consistently point to an extraterrestrial origin.

6. Interstellar Dust

6.1. INTERSTELLAR EXTINCTION

Identifying the composition of interstellar dust in clouds has been a high priority for astronomical research since the early 1930s (see Wickramasinghe, 1967). 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. The paradigm in the 1960s that the dust was largely comprised of water-ice was quickly overturned with the advent of infrared observations showing absorptions due to CH, OH, C–O–C linkages consistent with organic polymers. The best agreement for a range of astronomical spectra
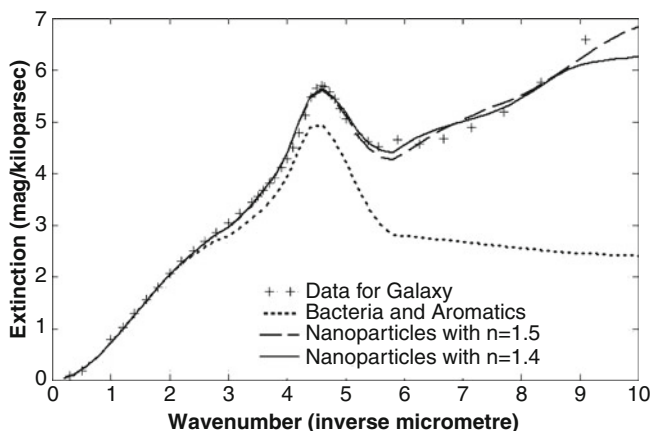
Figure 5. Agreement between interstellar extinction (+) and biological models. Mixtures of hollow bacterial grains, biological aromatic molecules and nanobacteria provide excellent fits to the astronomical data. The 2175A hump in the extinction is caused by biological aromatic molecules (See J. Wickramasinghe et al., 2009).

embracing a wide 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 was a mixture of desiccated bacteria, nanobacteria, including biologically derived aromatic molecules as seen in Fig. 5.

6.2. THE IDENTIFICATION OF PAH AND BIOLOGICAL AROMATICS

The distribution of unidentified infrared bands (UIBs) between 3.3 and 22 μm is almost identical in their wavelengths in very different emission sources, more or less irrespective of the ambient conditions. Most recent studies of UIBs for a large number of galactic and extragalactic sources have been obtained using the Spitzer Space Telescope (Smith et al., 2007). Figure 6a shows the spectra of a young planetary nebula and a proto-planetary nebula showing characteristic UIBs. Figure 6b shows the average Spitzer spectrum for 13 starburst galaxies displaying the same set of UIBs.

Whilst PAHs (polyaromatic hydrocarbons), presumed to form inorganically, are the favoured model for the UIBs, no really satisfactory agreement with available astronomical data has thus far been shown possible for abiotic PAHs (Hoyle and Wickramasinghe, 1991). This is a particularly serious problem if we require the UIB emitters and the 2175A absorbers to be the same. The latter requirement is of course necessary because it is the starlight energy absorbed in the ultraviolet band that is being re-emitted as UIBs in the infrared. The fact that biological aromatic molecules could act in such a dual role was noticed over two
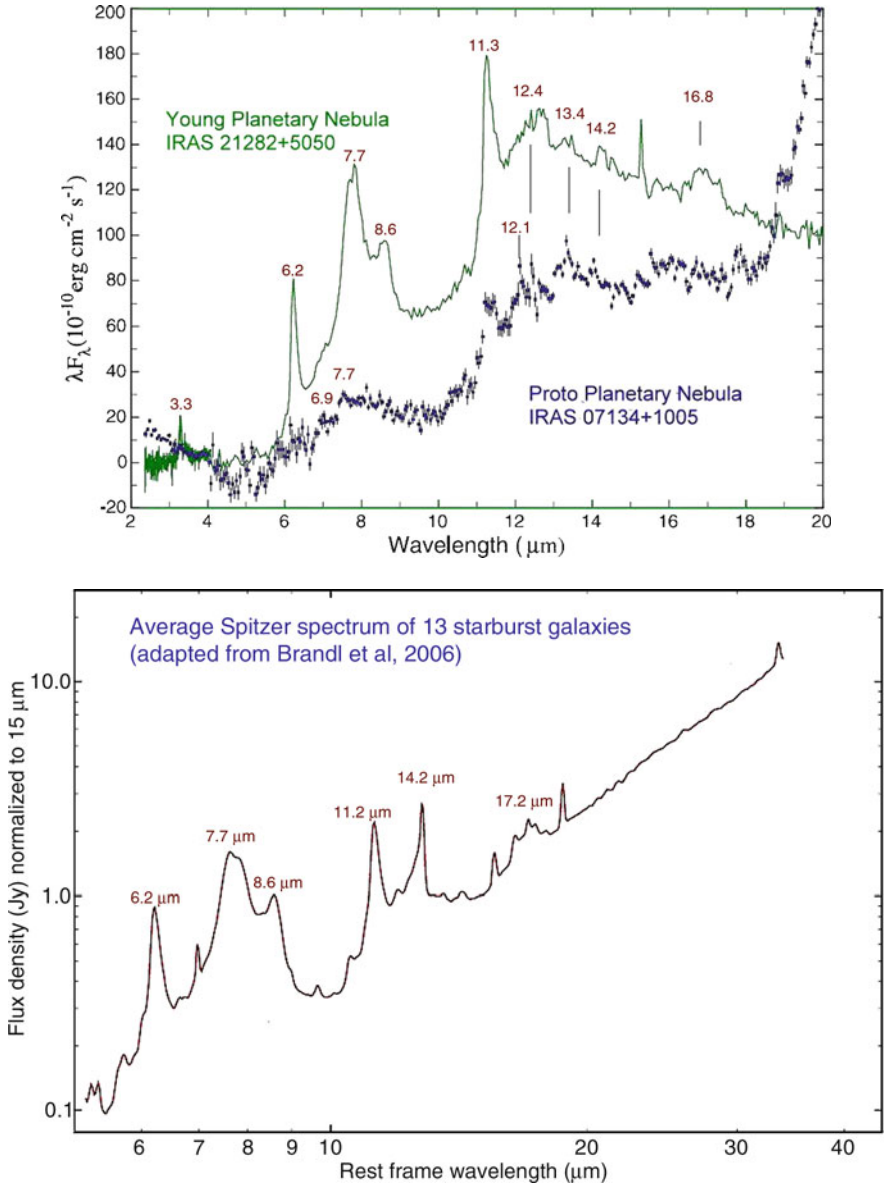
Figure 6. (a) *ISO SWS01* spectra of the young planetary nebula IRAS 21282+5050 and the proto-planetary nebula IRAS 07134+1005 (Adapted from Kwok, 2009). (b) Averaged *Spitzer* IRS spectrum of 13 starburst galaxies (Adapted from Brandl et al., 2006).
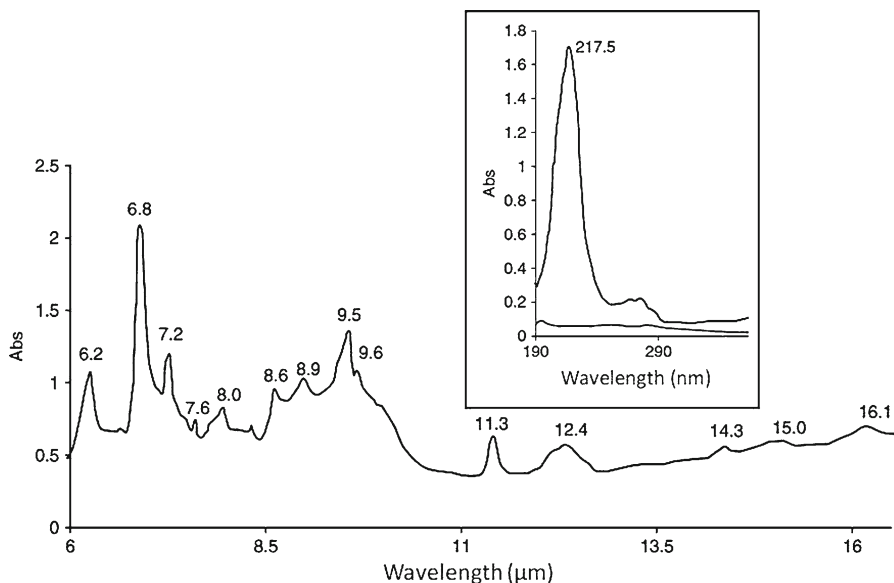
Figure 7. IR spectrum of algae in KBr. *Inset* is the spectrum of algae and degradation products in cyclohexane.

decades ago (Wickramasinghe et al., 1989, 1990). Recent laboratory studies by Rauf and the present author have provided further evidence favouring biology as seen for the case of algae in Fig. 7 (Rauf and Wickramasinghe, 2010).

Here we see a range of UIBs and the 2175A extinction feature arising from the same naturally occurring PAH system. A tabulation of the principal infrared bands for biological material for comparison with astronomical data is set out in Table 2 (Rauf and Wickramasinghe, 2010; Gezari et al., 1993).

Figure 8 shows a particularly interesting case where the spectrum of the Antennae galaxies at some 63 million light years distance has been observed to have infrared emissions that match the laboratory spectrum of anthracite (Guillois et al., 1999). Anthracite being a product of biological (bacterial) degradation is again indicative of biological particles, in this case at great distances from the Milky Way. Caltaldo et al. (2002) have shown that aromatic distillates of petroleum, another biological product, exhibit correspondences with the astronomical diffuse infrared bands (UIBs) as well as the λ2175A ultraviolet extinction feature.

6.3. OTHER SPECTRAL FEATURES

The most dramatic recent discovery relating to astronomical aromatic molecules is a conspicuous 2175A band in the lens galaxy of the gravitational lens SBS0909+532 which has a red shift of $z = 0.83$ (Motta et al., 2002). The extinction

Table 2. Distribution of two astronomical observations (UIBs and proto-planetary nebulae (PPNe)) and major IR absorption bands in laboratory models of terrestrial origin (Rauf and Wickramasinghe, 2010).

| UIBs	PPNe	Algae	Grasses	Bituminous coal	Anthracite coal
3.3	3.3	3.3	–	3.3	3.3
–	3.4	3.4	3.4	3.4	3.4
6.2	6.2	6.0	6.1	6.2	6.2
–	6.9	6.9	6.9	6.9	6.9
–	7.2	7.2	7.2	7.2	7.2
7.7	7.7	–	7.6	–	7.7
–	8.0	8.0	8.0	–	–
8.6	8.6	8.6	–	–	–
11.3	11.3	11.3	11.1	11.5	11.3
–	12.2	12.1	12.05	12.3	12.5
–	13.3	–	–	–	13.4
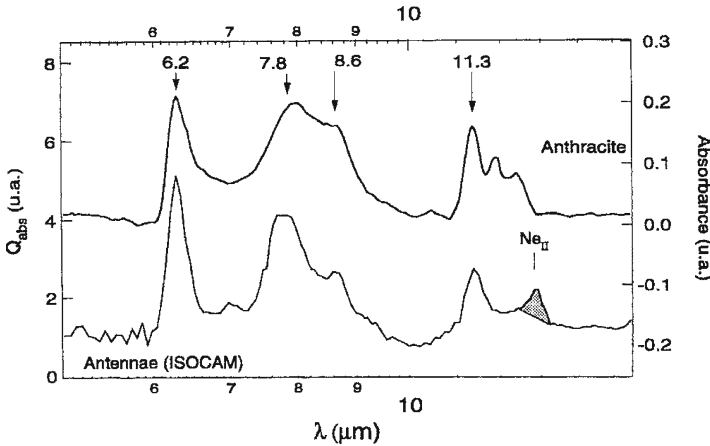
Figure 8. ISO spectrum of the Antenna galaxies compared with a spectrum of anthracite (Guillois et al., 1999).

curve for this galaxy is reproduced in Fig. 9, with the dashed curve representing a scattering background attributed to hollow bacterial grains.

The excess absorption over and above a pure scattering background (dashed curve) is normalised to unity at the peak and plotted as the points with error bars in Fig. 10. The curve in this figure shows the absorption of biological aromatic molecules similarly normalised (Wickramasinghe et al., 1989).

The match between the data points and the theoretical curve shows that biological aromatics are a viable explanation of an absorption feature in a galaxy located at a red shift of z = 0.83. This was an epoch when the universe was nearly half its present radius.
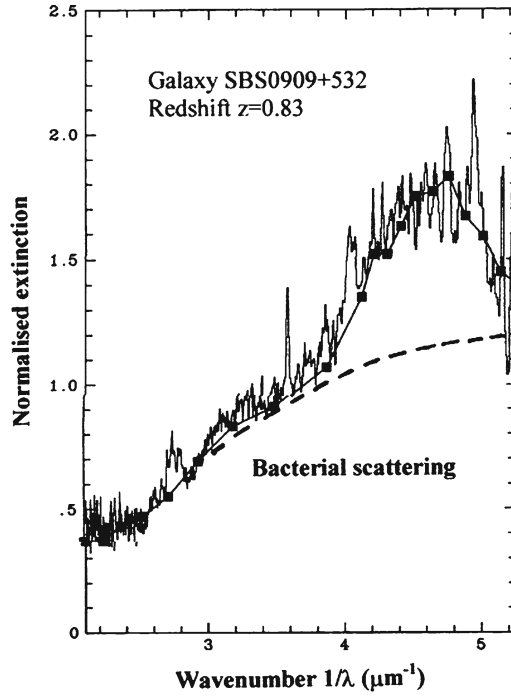
Figure 9. The *continuous line* is the extinction curve for the gravitational lens galaxy SBS0909+532 (Motta et al., 2002). The *dashed curve* is the scattering background attributed to bacterial particles.
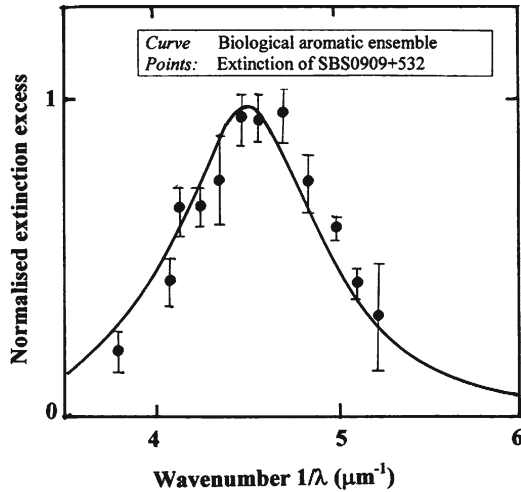
Figure 10. The *curve* is the normalised absorption coefficient of an ensemble of 115 biological aromatic molecules. The *points* are observations for the galaxy SBS0909+532 due to Motta et al. (2002), representing the total extinction shown in Fig. 9, from which an underlying bacterial scattering component has been subtracted.

6.4. FLUORESCENCE PROPERTIES AND MASS SPECTROSCOPY

In Sects. 6.2 and 6.3, we saw that biologically derived ensembles of aromatics can both UIBs and the 2175A extinction feature in interstellar material. The diffuse interstellar absorption bands in optical stellar spectra, particularly the 4430A feature, also have possible explanations on the basis of molecules such as porphyrins (Hoyle and Wickramasinghe, 1979; Johnson, 1971).

We now show that the so-called extended red emission of interstellar dust (ERE), showing up as a broad fluorescence emission band over the range 5,000–7,500 A, can be matched with biological pigments (Hoyle and Wickramasinghe, 1996; Wickramasinghe et al., 2002). Extended red emission (ERE) has been observed in planetary nebulae (Furton and Witt, 1992), HII regions (Sivan and Perrin, 1993), dark nebulae (Mattila, 1979) and high-latitude cirrus clouds (Szomouru and Guhathakurta, 1998) in the Galaxy as well as in extragalactic systems (Perrin et al., 1995; Darbon et al., 1998). This phenomenon has a self-consistent explanation on the basis of fluorescence of biological chromophores (pigments), e.g. chloroplasts and phytochrome. Competing models based on emission by compact PAH systems are not as satisfactory, as is evident in Fig. 11. Hexa-peri-benzocoronene is one of a class of compact polyaromatic hydrocarbons that have been discussed in the astronomical literature. However, the width and central wavelength of its fluorescent emission leave much to be desired.

Direct mass spectroscopy of interstellar dust in the Stardust mission (Krueger et al., 2004) has also shown the presence of cross-linked hetero-aromatic structures in the degradation products of impacting interstellar grains. Evidence of fragments with atomic mass unit AMU >2,000 consistent with pyrrole, furan substructures and quinones were found (Fig. 12). The fractured components of cell walls are arguably the only types of molecular structures that would survive impacts at speeds of ~30 km/s.

## 7. Comet Dust and Biomaterial

7.1. COMET SPECTRA

There is growing evidence to support the view that the composition of dust in comets is very similar to that of interstellar dust, a claim originally made by Vanysek and Wickramasinghe (1975). Since the exploration of comet Halley in 1986, the infrared spectra of cometary dust have been found to be consistent with an organic-biological grain model. This however does not imply the absence of water-ice, silicates or other inorganic materials in comets. Water-ice is indeed a major component of comets although silicates appear to be a relatively minor component.

Spectral features near 19, 24, 28 and 34 μm observed by ISO have been attributed to hydrated silicates in several proto-planetary discs, and in comet
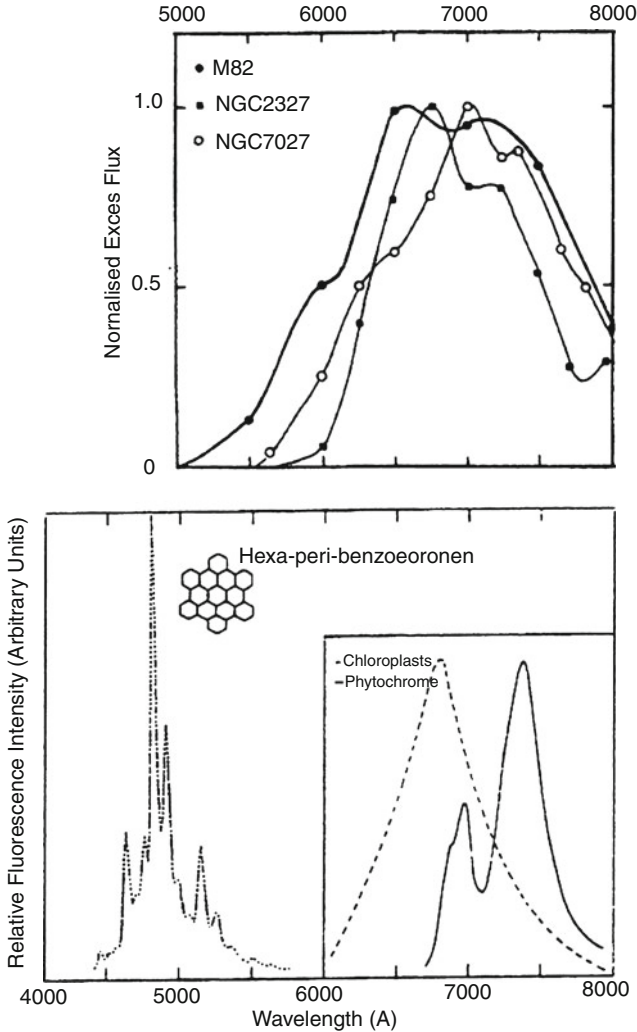
Figure 11. The points in the *top panel* show normalised excess flux over scattering continua from data of Furton and Witt (1992) and Perrin et al. (1995). The *bottom right panel* shows relative fluorescence intensity of spinach chloroplasts at a temperature of 77 K. The *dashed curve* is the relative fluorescence spectrum of phytochrome. The *bottom left panel* is the fluorescence spectrum of hexa-peri-benzocoronene.

Hale-Bopp (Crovisier et al., 1997; Waelkens and Waters, 1997). 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, such material could make up only some few percent of the mass of the dust, the rest being Trapezium-type grains – i.e. grains such as exist in the Trapezium nebula – which also, according to our
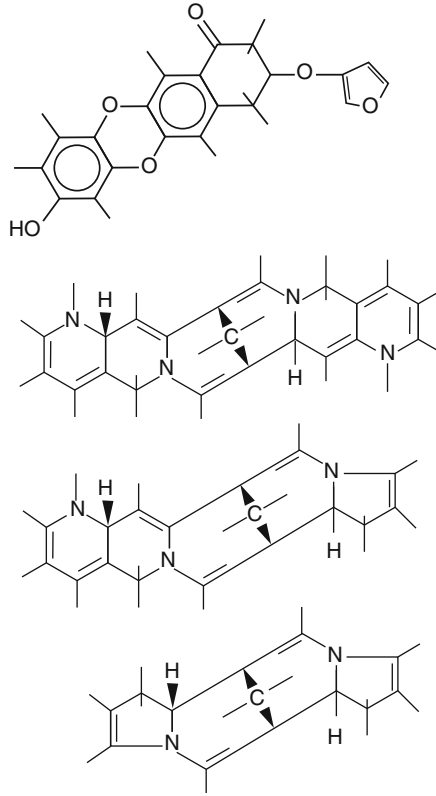
Figure 12. Functional groups in the break-up fragments of impacting interstellar dust grains, inferred by Krueger and Kissel (2000) from mass spectroscopy.

interpretations may be largely organic (Hoyle and Wickramasinghe, 1991). This appears to be the case for the infrared flux curve of comet Hale-Bopp, obtained by Crovisier et al. (1997) when the comet was at a heliocentric distance of 2.9 AU.

The dashed curve in Fig. 13 is for 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 than biomaterial, makes up only 10% of the total mass in this model (Wickramasinghe and Hoyle, 1999). It is interesting to note that the far-infrared emission spectrum of the proto-planetary disc around the star HD100546 has a strikingly similar spectrum to that of comet Hale-Bopp.

7.2. DIRECT ANALYSIS OF COMET DUST

The first in situ analysis of comet dust was carried out in 1986 for dust particles from comet Halley as they impacted a mass spectrometer on board the Giotto spacecraft at speeds of ~30 km/s (Kissel and Krueger, 1987). By analysing the
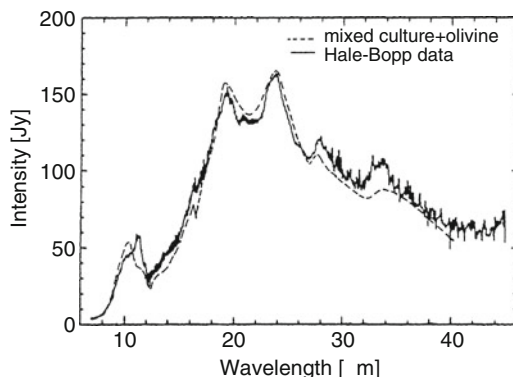
Figure 13. The infrared spectrum of comet Hale-Bopp obtained by Crovisier et al. (1997) when the comet was at a heliocentric distance of 2.9 AU (*jagged curve*). The *dashed curve* is for a mixed culture of microorganisms and olivine dust which comprised 10% of the total mass. The diatoms (diatomaceous silica) make up 20% by mass.

masses of break-up products, a large fraction of the grains were found to be organic ('CHON' particles) with compositions that included long-chain hydrocarbons and nitrogenated polyaromatic molecules. These molecular structures are fully consistent with the break-up of bacterial cells, although they do not of course prove such a composition unequivocally.

The claim originally made that bacterial particles are ruled out because the break-up material did not show evidence of the biologically important element phosphorus is flawed. Molecular ion-mass spectra of Kissel and Krueger (1987) could be interpreted as plausible combinations of P with other elements. The break-up of phosphorus groups (as in DNA) could lead to possible mass peaks corresponding to PO_3^+ (79), PO_2^+ (63) or PO^+ (47) rather than P^+ (31). That such evidence does indeed exist was shown in an analysis by one of the present authors (Wickramasinghe, 1993). The claim that mass peaks corresponding to two other biologically significant elements Na and K are too low for biology is also open to challenge. Although freeze-dried cultures of vegetative bacteria may be ~100 times richer in Na and K, this is not the case for nutrient-starved bacteria nor for spores (Wickramasinghe, 1993).

The Stardust mission to comet Wild 2 was launched in 1999, and the experiments it carried were planned over the preceding decade at a time when cometary microorganisms were dismissed as an outright impossibility. The protocol used for particle collection would not have permitted the survival of intact cells. In January 2004, the Stardust captured dust from the tail of comet Wild 2 in blocks of aerogel. Each particle impacted the aerogel at an initial speed of ~6 km/s, excavating a track along which break-up debris was deposited. Along the tracks, a wide range of organic molecules including the amino acid glycine was discovered. The detection of hetero-aromatic molecules rich in N and O could be a telltale sign of degraded biomaterial, biology being particularly rich in such structures.

The aerogel also showed evidence of pre-solar grains including a class of highly refractory minerals which probably condensed in supernovae explosions.

The Deep Impact mission that reached comet Tempel 1 on 4 July 2004 involved a high-speed impactor that crashed onto the comet's surface. The crust of the comet was thereby ruptured releasing subsurface cometary material that was analysed in situ. The Deep Impact mission found evidence of clay particles in comets for the first time, together with water and a range of organics (see, for instance, Fig. 1).

## 7.3. CAPTURE OF COMET DUST IN THE STRATOSPHERE

In both the Giotto and Stardust missions, cometary particles were examined and studied after they had endured high-speed impacts. Survival of fragile organic structures (e.g. bacteria) would have been virtually impossible in such conditions.

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. Although much of the incoming material burns up as meteors, a significant fraction survives entry. Micron-sized organic grains, 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 (Gregory and Monteith, 1967). Balloons and rockets reaching heights well above 50 km were deployed and 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 at this stage. No DNA sequencing procedure was available at the time to ascertain any significant deviations there might have been from terrestrial species. Moreover, 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 (Harris et al., 2002). 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
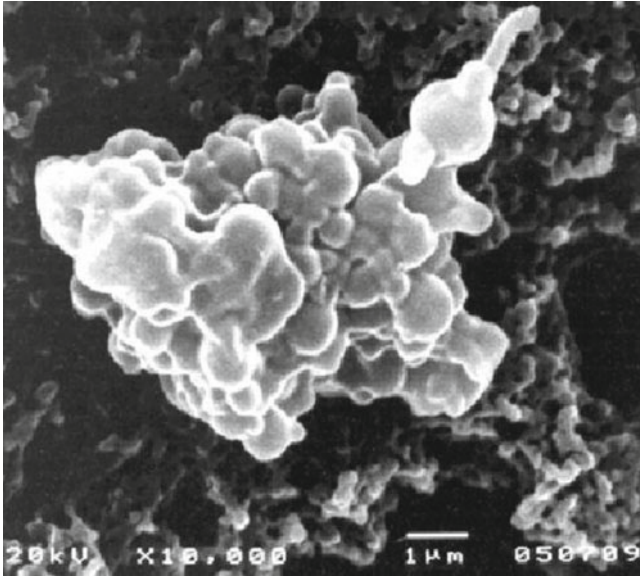
Figure 14. A carbonaceous stratospheric particle from 41 km resembling a clump cocci and a rod bacterium.

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 broad classes: (a) mineral grain aggregates, very similar to Brownlee particles, but somewhat smaller; (b) fluffy carbonaceous aggregates resembling clumps of bacteria (see Fig. 14). 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 shown in Fig. 14, 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 unambiguously by the use of a fluorescent 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 also cultured from stratospheric air samples by Wainwright et al. (2003), 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 S. Shivaji and his colleagues (Shivaji et al., 2009) yield cultures of 3 hitherto unknown microbial species which were highly resistant to ultraviolet light. Although a space origin is tempting to infer, contamination cannot be ruled out entirely and the jury is out on all these matters.

8. Microfossils in Meteorites

The topic of microfossils in carbonaceous chondrites has sparked bitter controversy in ever since it was first suggested in the mid-1960s (Claus et al., 1963). Since carbonaceous chondrites are generally believed to be derived from comets, the discovery of fossilised life forms in comets would provide strong prima facie evidence in support of the theory of life in comets and cometary panspermia. However, some contamination was discovered in the original samples, and claims that all the micro-structures (organised elements) discovered in meteorites were artefacts or contaminants led to a general rejection of the microfossil identifications in the 1960s.

The situation remained uncertain until early in 1980 when H.D. Pflug found a similar profusion of 'organised elements' in ultra-thin sections prepared from the Murchison meteorite, a carbonaceous chondrite that fell in Australia on 28 September 1969 (Pflug, 1984). The contaminant free experimental methods adopted by Pflug were 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.
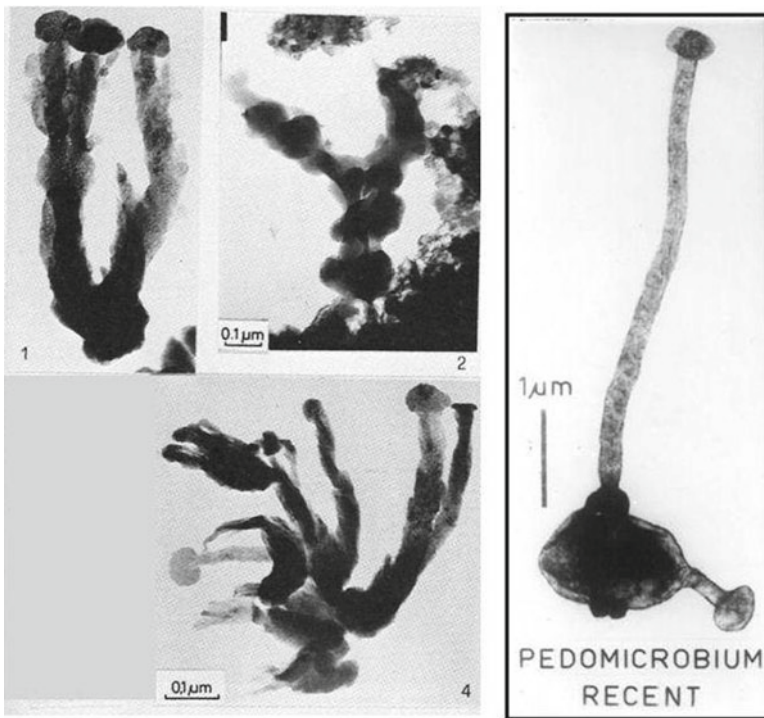
Figure 15. Microfossils in the Murchison meteorite discovered by H.D. Pflug (1984).

Living cyanobacteria   Microfossils in Murchison
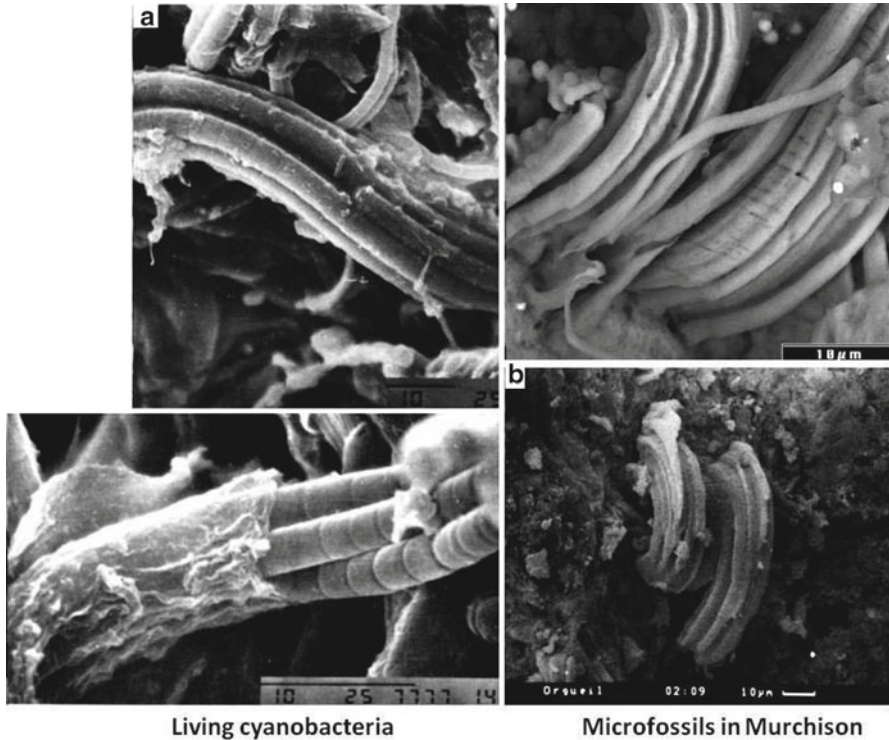
Figure 16. Structures in the Murchison meteorite compared with living cyanobacteria (Hoover, 2005).

Figure 15 shows examples of Pflug's findings. Not only were these morphologies strikingly characteristic of particular types of fossil microbes, but laser ion probe analysis yielded compositions of these structures that were also consistent with life. These studies made it very difficult to reject the fossil identification. More recent work by Richard Hoover (2005) and his team now leaves little room for any other interpretation of these structures than that they are microbial fossils (Fig. 16).

9. Concluding Remarks

At the end of a century of scientific exploration of the question life's origins from Arrhenius and Oparin to the present day, the problem remains essentially unsolved. If honesty prevails, one has to admit that the precise steps that may have led from organic chemicals to the simplest self-replicating microorganisms are unknown. The transition from non-life to life involves improbabilities of an astronomical or even super-astronomical order. To assert without proof that this must have taken place on our minuscule speck of a planet, Earth, against all the odds, is

tantamount to reviving a pre-Copernican philosophy. We argued in this chapter that a first origin of life most probably involved the resources of a large fraction of the observable universe, possibly within the warm interiors of comets or icy planets very early in the history of the universe.

The profusion of biogenically relevant organic molecules that exist over a large part of the observable universe (Kwok, 2009) is incorrectly interpreted as arising from 'prebiotic processes'. The correct interpretation, in the view of the writer, is that panspermic processes continue to distribute living cells from a single cosmic origin of life. What is observed astronomically in interstellar clouds in our galaxy and in external galaxies are molecules representing the detritus of living cells.

Carbonaceous meteorites, such as the Murchison meteorite, also carry a vast array of exceedingly complex organic molecules that could represent the decay products of life. Because amino acids in terrestrial life are left-handed and sugars right-handed, the chirality of meteoritic material would in principle differentiate biotic and abiotic origins. However, chemical changes accompanying the fossilisation tend to switch the handedness and racemise biomaterial. The confirmation of achirality in uncontaminated meteoritic material, with 10–20% left-handed excess (Pizzarello, 2004), presents a serious difficulty for advocates of an entirely abiotic origin of these molecules. The amazingly rich diversity of organics identified in the Murchison meteorite (Schmitt-Kopplin et al., 2010) likewise comes as no surprise in the context of cometary panspermia and is difficult to explain otherwise. If cometary bodies (the parent bodies of meteorites) are carriers of microbial life, one expects a diversity of organic molecules far richer than that which prevails on Earth, generated more via biological than prebiotic processes (Wickramasinghe, 2010). We conceive that extraterrestrial biology carried by comets with diverse initial complements and histories could represent a far greater variety than the minute subset adapted to terrestrial environments and surviving competitive evolution. Even if the question of achirality is ignored, the observed extent of diversity of molecules in the Murchison meteorite – in excess of highly chemically diverse petroleum processes (Schmitt-Kopplin et al., 2010) is improbable to arise from abiotic processes.

To sum up, a wide range of data from astronomy, geology, meteorite studies and microbiology all point to a cosmic origin of life and provide strong support for panspermia. The emerging paradigm is that the origin of life was a unique cosmological event that was accomplished within planetary interiors or within interiors of cometary-type bodies within a few million years of the Big Bang (Gibson et al., 2010).

However, our understanding of the processes involved in this first event of origination still remains far from complete and might well remain so for generations to come (Abel, 2006). What is certain is that a multiplicity of origination events can be excluded from the domain of plausible hypotheses. Comets remain the prime candidates for being the carriers and amplifiers of cosmic life. The Earth was seeded with such life from which we are descended some 4 billion years ago

and continues to be seeded even to the present day. On this picture, self-similar life forms must exist abundantly throughout the entire universe. We are by no means alone. Our genetic ancestors are scattered as cosmic dust across the vast reaches of the cosmos.

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