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A Short History of Panspermia from Antiquity Through the Mid-1970s

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Abstract

Panspermia is the philosophical proposition that the precursors of life are present in space and able to initiate life on reaching a suitable environment (especially the Earth). Only in the past century has the subject advanced from the lowly status of a dreamy hypothesis to a vibrant new science that is testable and observable. This history of panspermia presents the major figures associated with such hypotheses. It examines their motives, methods, and arguments, situated when possible in their historical context and culture rather than their impact on the present. From antiquity to the early modern period (1500–1800), the debates on the plurality of worlds and panspermia overlapped considerably. In the later modern period (1800 to the present), the narrative thread interweaves panspermia with the origin of life and the theory of evolution, and we can see authentic inputs from scientists rather than philosophers. In the interests of concision, I have omitted topics such as the Search for Extraterrestrial Intelligence, the exploration of the solar system by probes and landers, planetary protection (the inverse of panspermia), and the discovery of exoplanets. The historical literature is sometimes confusing: to correct for that, I have personally examined the original sources of every work cited rather than simply accepting the published findings of other scholars at face value. Key Words: Interplanetary transfer of life—Habitable planets—Plurality of worlds—Panspermia. Astrobiology 22, 1379–1391.

1. Prelude: Antiquity

Conventional histories of panspermia begin in the fifth century BCE with the natural philosopher Anaxagoras (500–428 BCE), a Presocratic Athenian, whose work—in common with all the Greeks that preceded Socrates—survives only in fragments and laudatory testimonials by later philosophers. The ancient Greek πανσπερμία translates as a mixture of all seeds. In a partial reference to panspermia, we find that Anaxagoras believed the following:

> were created by the fall of ''seed'' from heaven to earth, and afterwards by reproduction. The seeds of plants were likewise in the air, and were washed down by rain on to the ground, there they took root, and became ''living things attached to the ground'' (Freeman, 1966)

In the 20th century, a consensus arose among classicists that Anaxagoras had imagined the entire Cosmos to be full of seeds of life, and the animals were created by the fall of *spermata* from heaven to earth. Importantly, the panspermia theory that Anaxagoras was proposing in the fifth century BCE was not metaphysical, but thoroughly physical. Robert Temple, in a colorful, informative, and witty romp through the polytheistic proto-panspermian heavenly realms of the Greeks, the Pharaohs, and the Gnostics, even dares to suggest that Anaxagoras' concept was astrophysical (Temple, 2007).

A little later in antiquity, the early Greek atomists Leucippus and Democritus (c. 470–360 BCE) posited the existence of an infinite number of worlds (meaning realms of existence). The evidence we have for this thesis is thin, mostly consisting of passing mentions in much later classical sources. A member of the school of Democritus, Metrodorus of Chios (fourth century BCE), wrote that it was unlikely that an infinite universe would include only one world, picturesquely describing it as unlikely as finding a

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single ear of corn growing on a vast plain (Guthrie, 1965). By the third century BCE, Epicurus (341–270 BCE) had founded an eponymous movement based on empiricism. Deriving his cosmology from Democritus, he likewise taught that the universe is infinite. The Epicurean atomistic view embraced limitless time, endless space, and an infinite number of everlasting parcels of moving matter.

It does not imply, however, that the universe is populated by other sentient beings (Warren, 2004). Epicurean philosophy was powerfully altruistic, placing an extremely high value on friendship (love). Both Democritus and Epicurus imagined an infinite cosmos in which all the natural phenomena—including life—would be possible. Lucretius (~ 99–55 BCE), a Roman poet and philosopher, transmitted the ideas of Epicureanism in his poem *De rerum natura* in which one can read his opinion that ''Nothing in the universe is unique and alone, and therefore in other regions there must be other Earths inhabited by different tribes of men and breeds of beasts …'' (Sedley, 2018).

However, it is important to recall that the panspermia of the ancients is not our panspermia. (Likewise, the Cosmos and the cosmologies of long ago do not meld seamlessly into our world picture.) The term panspermia was not used as an explanation of the origin of life until the early 20th century. As academics, when we engage in our outreach and public activities to attract the curious onlooker, we should avoid viewing the world of the ancient cultures through the lens of modernity. It is erroneous to endorse the past by overprinting it with our present knowledge. The distinguished Scottish classical scholar W.K.C. Guthrie FBA (1906–1981) held and taught that the philosophy of the ancients should be interpreted in its *own* historical landscape rather projected into *our* canon of modern philosophy (Lloyd, 1982).

2. Two Millennia Later: A Plurality of Worlds

The concept of a plurality of worlds did not appeal to early Christian scholars. Albertus Magnus (1193–1280) and his pupil Thomas Aquinas (1225–1274) opposed the materialistic philosophy of the atomists, preferring instead the sublime abstract philosophy of Plato and Aristotle, the two central figures in Raphael's fresco *The School of Athens* (1509–1511). In March 1277, Bishop Étienne Tempier (1210–1279) of Paris issued a Condemnation prohibiting the teaching of 219 philosophical and theological propositions on concepts being disputed by the masters of the Faculty of Arts at the Sorbonne.

By condemning doctrines that placed serious limitations on God's absolute power, Tempier's syllabus of errors unleashed a massive assault on the Aristotelians at the University of Paris (Grant, 1969). Prominent Parisian philosophers who took advantage of this liberalization include Jean Buridan (c. 1295–1358) and Nicole Oresme (c. 1325–1382). Although they would oppose the ideas of a plurality of worlds, their arguments against Aristotle and Aquinas prevailed.

The doctrinal stance pivoted in 1440 when Nicholas of Cusa (1401–1464) published his early work *De docta ignorantia* (*On learned ignorance*), the essence of which was that the human mind needs to discover its ignorance of the Divine Being. In a rudimentary cosmological speculation, he conjectured the following:

> Life, as it exists on earth in the form of men, animals and plants, is to be found, let us suppose, in a higher form in the solar and stellar regions. Rather than think that so many stars and parts of the heavens are uninhabited and that this earth of ours alone is peopled—and that with beings, perhaps of an inferior type—we will suppose that in every region there are inhabitants, differing in nature by rank and all owing their origin to God, who is the centre and circumference of all stellar region … And we may make parallel surmise of other stellar areas that none of them lack inhabitants, as being each, like the world we live in, a particular area of one universe which contains as many such areas as there are uncountable stars. (Cusanus, 1440/1954)

The next advance in the promotion of plurality was the Copernican revolution of the mid-16th century that led to the emergence, in the following century, of multiple speculations and ingenious imaginations on the existence of intelligent extraterrestrials, generally buttressed by a doctrinal framework. Giordano Bruno (1548–1600) enthusiastically led the charge by championing Copernicus, promoting his plenitude of divine provenance and his populating of planets and stars. Some scholars have suggested this vigorous campaign was not the proximate reason for his fiery execution at the Campo de' Fiori in Rome: his fatal heresies were his denial of Christ's divinity and his alleged diabolism (Crowe, 1997). However, more recent scholarship that is based on a close reading of the extant source documents has admirably confirmed that the heresy of many worlds was the major issue in his trial, resulting in the consequential cruel and unusual punishment (Martinez, 2016).

René Descartes (1596–1650), in a letter written in 1657, hesitantly advanced a theological argument on the nature of redemption, stating that

> I do not see … that all the advantages that God has brought forth for man, obstruct him from having brought forth an infinity of other very great advantages for an infinity of other creatures. And although I do not at all infer from this that there would be intelligent creatures in the stars or elsewhere, I also do not see that there would be any reason by which to prove that there were not … (Descartes, 1657/1903)

Skeptical chemist Robert Boyle (1629–1691), 7th son and 14th child of the first Earl of Cork—the richest man in Britain—introduced experimentation and observation to chemistry. For his experiments on plant growth, he selected spring water rather than rainwater,

> … because the latter is more discernibly a kind of panspermia … yet seems to contain in it, besides the steams of several bodies wandering in the air, which may be supposed to impregnate it, a certain Spirituous Substance, which may be extracted out of it, and is by some mistaken for the Spirit of the World Corporify'd. (Boyle, 1661/2021)

Although it is an exaggeration to claim that Boyle swept aside alchemy and paved the way for modern chemistry, in the second edition of his somewhat muddled *Sceptical Chymist*, he speaks respectfully of the higher order chemists with their ability to transmute base metals. By questioning commonly held chemical theories, Boyle aimed to raise chemistry to the status of a real science, for the exploration of the hidden realms of nature. According to the Oxford English Dictionary, *panspermia* in the quote immediately above should be read in the original Greek sense of a ''universal source or cause'' (Principe, 2011).

Our narrative now moves to Bernard Le Bouvier de Fontenelle (1657–1757), who had the misfortune to miss his birth centenary by 32 days; he became an esteemed academician, celebrated in the highest rank of French intellectual society at the dawn of the Age of Enlightenment. An outspoken supporter of Cartesian physics, he enters our narrative through his accessible and influential work on the plurality of worlds (Fontenelle, 1686/1803). This sensational bestseller envisioned an infinite universe of planetary systems, each having formed in a Cartesian vortex.

The narrative structure of the short book is a series of informative evening conversations between a savant (Fontenelle, naturally) and a curious, but incredulous Marquise (a married woman from the second rank of the French nobility). *Entretiens sur la pluralité des mondes* gives a lively account of the origin of the solar system—Sun, Moon, and planets—that is intelligible to the ordinary reader without being patronizing. It was through this book that Fontenelle popularized for French readers the astronomical theories that Descartes had elaborated in 1644 (Descartes, 1644). In the final section of the book, Fontenelle enthusiastically expounds on the plenitude of planets. An ''infinity of vortices'' has led to the condensation of planets on a scale that implies ''we are thus lost among millions of worlds'' (Descartes, 1659).

Despite its soaring success in delighting the salons of Paris, the clerics in Rome condemned the work as dangerous, putting it on the Index in 1687, which in practice made no difference to its impact beyond Rome and the Papal States. By the close of the following century, it would be translated into nine languages and published in dozens of editions.

3. The Extraterrestrial Life Debate in the Age of Enlightenment

In 1698, Fontenelle's elegant narrative on extraterrestrials became eclipsed by the leading continental scientist of the 17th century, Christiaan Huygens (1629–1696) of The Hague. This great physicist, mathematician, and astronomer was a major figure in the scientific revolution whose posthumous book *Cosmotheoros* (*The celestial worlds discovered*) speculated on the existence of life, similar to that on Earth, on other planets (Huygens, 1697). Huygens argued that water is essential to life and considered that his observations of white markings on Mars and Jupiter were evidence of water ice on those planets (Simonyi, 1978/2012).

By the dawn of the 18th century, Huygens' *Cosmotheoros* was accessible in five languages, and the European intellectual and philosophical movement known as the Enlightenment was in full swing. Central to the ethos of this Age of Reason was the concept that *reason* alone has the power to enable humanity to *understand* the universe and to improve the human condition. In the earlier centuries, the Renaissance and the Protestant Reformation of northern Europe had challenged and undermined the monolithic authority and received wisdom of the Church. In the sciences, empiricism, rational thought, and the scientific method replaced authority.

Robert Hooke (1635–1703) and Antoni van Leeuwenhoek (1632–1723), admirably demonstrated the power of the scientific method by applying their microscopes to the examination of microorganisms. Hooke's *Micrographia* published in 1665 has the first description and illustration of a microbe in the scientific literature (Hooke, 1665). *Micrographia* has 38 exquisite engravings: the tradition of visual communication in science largely begins with this beautiful book (Chapman, 2005). In April 1673, Leeuwenhoek began a lengthy correspondence to the Royal Society of London, where Hooke was Curator of Experiments from 1662 (Gest, 2007).

From 1677, when he was appointed Secretary, Hooke received Leeuwenhoek's correspondence and replied on behalf of the Society. He conducted experiments to confirm Leeuwenhoek's observations of ''little animalcules'' — protozoa and bacteria (Lane, 2015). Hooke was well aware of one momentous implication for biology: the existence of an abundance of microscopic life. In December 1677, he signed off a letter with a flourish: ''Your very great admirer and honorer, Robert Hooke'' (Gest, 2009). Hooke and Leeuwenhoek had a major impact on the extraterrestrial life debate by demonstrating that life was far more complicated and much richer than had been imagined. Although Leeuwenhoek's discoveries took a few decades to move the debate along (because he was so secretive), his ability in instrumentation and experimentation for advancing microbiology would not be surpassed until the 19th century.

Unsurprisingly, the extraterrestrial life debate attracted the attention of many poets, philosophers, astronomers, and theologians during the Enlightenment and, later, the flourishing of Romanticism. Dick (1996) and Dick (1982) and Crowe (1988) give comprehensive summaries of the ongoing debates in their monographs.

Celebrated contributors included Immanuel Kant (1724–1804) who incorporated extraterrestrial commentary in nine of his books; François-Marie Arouet (1694–1798, *nom de plume* Voltaire) who mentions it in numerous publications; the stellar astronomers Thomas Wright of Durham (1711–1786) and William Herschel (1738–1822); and the English-American pamphleteer and revolutionary Thomas Paine of Norfolk (1737–1809) who acknowledged that a higher power (Creator) must have populated the planets, but then roundly ridiculed the logic of Christian doctrine on these matters (Paine, 1794–1795/1961). The close of the 18th century is a convenient point at which to bring the field of panspermia *per se* into this historical record as a legitimate topic of scientific enquiry.

4. Meteorite Falls in France: A Source of Extraterrestrial Organics?

In the early 19th century, the first systematic investigations of meteorites took place in France, where three remarkable meteorite falls transformed skeptical enquiry into a new kind of science. We will start in the lively market town of L'Aigle in rural Normandy, north-western France, where the population was almost 6000 according to the census of 1800. On April 26, 1803, a spectacular cascade of 3000 stones rained down from the clear blue sky. Many astonished citizens witnessed this fall. Two months later, the dramatic news finally reached Paris, and the ear of the First Consul of France, Napoléon Bonaparte. His minister of the interior, Jean-Antoine Chaptal (1756–1832), a brilliant multidisciplinary scientist, commissioned a full investigation by

Jean-Baptiste Biot (1774–1862), a young professor of mathematical physics at the Collège de France.

Biot conducted his enquiries through impressive field work, and by taking witness statements from travelers, coachmen, clergymen, and citizen professionals about the ‘‘rain of stones thrown up by the meteorite.’’ Biot’s report set out clearly the evidence that those fallen stones were of *extraterrestrial* origin, rather than caused by an atmospheric or volcanic phenomenon. He cited the physical evidence of the absence locally of any stone or artifact similar to the 37 kg of some 3000 fallen stones, as well as the testimonies of reliable eyewitnesses. The L’Aigle fall became the touchstone in the development of our understanding of meteorites and their extraterrestrial origins (Biot, 1803).

A turning point had in fact been missed earlier in 1794, when German physicist Ernst Chladni (1756–1827) published a 63-page book claiming that meteorites were of extraterrestrial origin, despite his never having seen one fall, or indeed handled one (Chladni, 1794). Chladni had carried out desk research on reports of fireballs and meteor falls in ancient and modern literature.

Although there were plenty of witness reports on dazzling fireballs, he was only able to track down 18 witness reports of actual falls in all of history. Chladni, who had trained as a lawyer, only turned to natural philosophy on the death of his father in 1782. His legalistic deductive approach led him to naive acceptance of historically documented witness reports as scientific fact. He concluded that meteors, fireballs, and meteorites are different manifestations of the same phenomenon: the entry into Earth’s atmosphere of a solid extraterrestrial object, a relic from the formation of planets (Marvin, 1996)! This hypothesis was highly controversial at the time: Chladni was ridiculed by his peers. Biot, by contras report enjoyed an enthusiastic reception because his report demonstrated due diligence: written statements from educated witnesses, thus avoiding the cliché of picking up the gossip of *les paysans* (Gounelle, 2006).

The next big story broke toward dusk on March 15, 1806. *Paysans* toiling in fields near to Alais in southern France (now Alès, Gard, in Occitanie) were awestruck by a ‘‘great vividness seeming to be made by a cannon shot which was preceded by a terrible rumble of thunder,’’ as two stones weighing 4 and 2 kg thudded to earth. The stones were so friable that the locals wondered if they were carbonized peat. Later that year, Louis Jacques Thénard (1777–1857), professor of chemistry at the Collège de France, published a chemical analysis of the Alais fall, assessing the carbon content as 2.5%, marking it out as an unknown kind of space rock (Thénard, 1806).

Alais was the first meteorite to be recognized as a carbonaceous chondrite, a distinctive class: relative to ordinary chondrites, just 3.8% are classed as carbonaceous. Superficially, they are deceptively similar to today’s barbeque briquettes: frangible, highly porous, and brimming with soluble minerals. Six months in the open in a wet climate leads to their disintegration, which is why the immediate recovery of the L’Aigle meteorite was extraordinarily important. Ordinary chondrites are deficient in volatiles because they were formed in a high-temperature environment. Carbonaceous chondrites contain water up to 20% by mass as mineral hydrates and are generally richer in volatiles overall.

The distinguished Swedish chemist Jöns Jacob Berzelius (1779–1848) identified water in a meteorite in 1834, becoming the first scientist to do so. Probing further, he isolated a blackish mess that was 12% elemental carbon. Acting with commendable reluctance, Berzelius concluded that the presence of organics in the meteorite indicated the material had originated in space or from other planets. The conjecture that life existed elsewhere was no longer a dreamy conjecture; it had become a hypothesis that could be tested empirically (Berzelius, 1834).

France turned up trumps for the third time on May 14, 1864, when a spectacular fireball as bright as the full Moon was observed all over western France. Twenty fragments from an exploding bolide crashed into the hamlet of Orgueil, 54 km north of Toulouse. This time, the dramatic news spread rapidly by mail coach. In Paris, the Academy of Sciences acted with alacrity: two letters reporting the observations were read at the Academy just days later. The first newspaper coverage appeared on May 17 in Montauban, the nearest city to Orgueil. A retired professor of natural philosophy at Toulouse described a stone about the size of an orange that he had grabbed. This handy specimen was fragile, with a strong varnish. He plunged it into a bucket of water, perhaps wanting to measure its density, but it dissolved into mud as black as shoeshine (Gounelle and Zolensky, 2014)!

Chemists and mineralogists in Paris and Toulouse quickly implemented a network approach to investigate the Orgueil fall. The many witness reports generated intense activity, and the professionals were spurred on to act decisively by reports of the fragility of samples. At that time, France’s leading expert on meteorites was Gabriel Auguste Daubrée (1814–1896) of the National Museum of Natural History. As the curator of meteorite collections, he received numerous witness reports about the Orgueil fall from all over western France, as did Urbain Le Verrier (1811–1877) at the Paris Observatory.

Daubrée and his Parisian associates convened a consortium to study the properties of the new meteorite. Specimens were distributed and tasks allocated. Drawing on his experience as a curator, Daubrée classified Orgueil with Alais and two other carbonaceous chondrites. He informed the Academy on May 30 that it is ‘‘not only tender and friable but also disintegrates into an impalpable dust as soon as it is put in contact with water.’’ The chemist Stanislas Cloëz (1817–1883) announced the first chemical analysis, reporting the presence of salts at 5.30% and a carbon content of 5.92% (Cloëz, 1864b). Five weeks later, Cloëz gave a fuller account of the carbonaceous substances that he had extracted with boiling hydrochloric acid. He noted that the insoluble organic matter ‘‘looks very much like humus of some earthy carburant … analogous to peat or lignite’’ (Cloëz, 1864a).

Meanwhile, the Toulouse branch of this meteoritic carbon network, likewise engaged in research, reported finding that complemented those of their Parisian colleagues. Two of the Toulouse scientists commented that, ‘‘had they put together all the stones they were presented they would have made the load of a donkey,’’ a picturesque unit of measurement to use 70 years after the adoption of the metric system! The donkey work would have weighed 50 kg. In 1867, Daubrée published the definitive review of scientific investigation of the meteorite (Daubrée, 1867).

He viewed the richness of organic matter as a prominent property of the Orgueil meteorite, and cautiously proposed that they offer "a carbonaceous combination in a planetary body, where nothing proves so far the existence of organized beings, animal or vegetal." This proposition eliminated the old hypothesis of a lunar volcanic origin for the meteorites. Daubrée estimated the mass of stones recovered for scientific analysis as 15 kg. Today, the surviving fragments from the Orgueil fall can be admired in collections in Paris, Montauban, Toulouse, Prague, and New York.

5. Origin and Evolution of Life on Earth: Extraterrestrial Queries

The fascinating evidence for organics (carbon chemistry compounds) in meteorites in the first third of the 19th century finally eliminated metaphysics from the extraterrestrial life debate. For a century thereafter, questions on the origin of life and its evolution transformed the discourse on panspermia. Was life universal? An intrinsic property of the universe? Where and how did it originate and propagate?

Some historians credit the widely travelled French diplomat Benoît de Maillet (1656–1738) as the philosopher who transposed the panspermia of antiquity to its modern form (Wainwright and Alshammari, 2010). It seems that he was familiar with the findings of Hooke and Leeuwenhoek when he wrote imagined conversations between a fictitious oriental mystic and a nonfictitious Frenchman (himself). In the Third Conversation, they imagine that space is full of the seeds of everything that can live in the universe.

De Maillet then elaborated this pre-Socratic argument by imagining that the uncountable number of animals and species (in reality algae and protozoa) that can be seen in a drop of water under the microscope are the precursors of lifeforms just like humans. They are transmitted through the universe and become concentrated by gravity onto rocky planets. Although de Maillet's fantastic speculation probably gained a polite hearing in narrow esoteric circles, he, being fearful of incensed clerics, left his article unpublished until it saw the light of day in Amsterdam 10 years after his death (De Maillet, 1748). The first edition in Enlightenment Britain came off the press in 1750 (De Maillet, 1750).

During the mid-19th century, there were dramatic improvements in our understanding of the origin of life and its evolution. Charles Darwin (1809–1882) was an undergraduate at Cambridge studying classics and theology when he was offered a summer job in 1831—an internship—assisting one of the founders of modern geology, Adam Sedgwick (1785–1873). Under Smith's tutelage, Darwin found natural history more compelling than natural theology. Several months later, in December 1831, 22-year-old Darwin joined the Royal Navy's HMS *Beagle* as the ship's naturalist and "a well-educated scientific person," according to the manifest. Five years later, when *Beagle* returned, Darwin was on the road to glory with his animal and botanical collections together with detailed field notes.

In his notebook, *Transmutation of Species* (July 1837), Darwin penned "I think" above his sketch of the "tree of life" encompassing all species. For the next 20 years, he worked incessantly on evolution, marveling at the ability of species to flourish in "diversified places in the economy of nature" (Pearce, 2010). The theory presented in 1859 in *Origin of Species* built on the work of many predecessors: Darwin acknowledged 34 authors in his sixth edition. *Origin of Species* was an instant success, the first printing selling out on publication day.

In 1864, the expression "survival of the fittest," first appears in the literature, in Herbert Spencer's landmark textbook *The Principles of Biology* (Spencer, 1864). Darwin thought the catch phrase a capital idea, adopting it for his fifth edition in 1869. A decade later, the author and educator Arabella Buckley (1840–1929), who was acquainted with Darwin, popularized adaptive evolution in beautiful children's books with catchy titles. Her *Winners in Life's Race* proclaimed the novel evolutionary science of vertebrates through an enchanting narrative that draws on the importance of adaptation to changing environments across geologic time (Buckley, 1883).

When Louis Pasteur (1822–1895), chemist and microbiologist, commenced his long series of experiments on fermentation, the notion of spontaneous generation prevailed in discussions on life's origin. Pasteur demonstrated that fermentation of grape juice is caused by yeasts (Hollinger, 2016). Félix-Archimède Pouchet (1800–1872) became the dominant proponent of spontaneous generation in France, and he believed that inanimate air enabled the spontaneous generation of living organisms in liquids. Pasteur triumphed in 1862 when the French Academy settled the debate in his favor, a decision that had a paradoxical consequence.

If simple microbial life could not arise from nonliving materials under the conditions existing on Earth today, where did it arise? Pasteur suggested "that there is in ordinary air something that is a precondition of life" (Pasteur, 1922). This was not panspermia as such, but "its corollary was that life would seem always to be derived from life," a sentiment that Fred Hoyle (1915–2001) and Chandra Wickramasinghe would reflect on 120 years later (Hoyle and Wickramasinghe, 1981). Those who supported Pasteur were thus bound to accept that *life* arose from *life*, which implied that life in the universe did not have an origin: life had always existed on some planet, somewhere. And the consequence hinted that organisms had travelled through space, from planet to planet, by some means unknown.

According to Kamminga (1982), the problem of the origin of life in universe had thus become a problem in physics through the discoveries of Pasteur and Darwin: "it was from physical scientists that theories of interplanetary transfer became prominent after a somewhat obscure beginning" (Kamminga, 1982). More recent scholarship by Réné Demets (2012) has argued that: "*The Origin of Species* not only kick-started the scientific development of the panspermia theory in the 19th century but [also] that biological evolution was an integral building block of it" (Demets, 2012).

6. The 19th Century: Birth of the Modern Panspermia Hypothesis

An early literature review of Darwin's teachings by the German botanist physician and editor Hermann Richter (1808–1876) revived the ancient idea that life is a fundamental feature of the universe (Richter, 1865). Richter suggested the possible development of life first in an extraterrestrial location, followed by transfer to Earth.

Richter's proposal marks the start of the modern panspermia hypothesis. As a co-editor of an annual review published in Leipzig, Richter reported on domestic and foreign advances in medical science. He praised Darwin's radical theory of evolution by natural selection for its clarity and simplicity, and its potential for elaboration in scientific terms.

Nevertheless, he was unimpressed by the lack of an explanation of the primordial cell type that must have been the necessary common ancestor. Citing ''the new astronomy''—and the conservation laws of physics—Richter regarded the existence of organic life in the universe as eternal: he thought seeds or germs could travel through space. Noting that carbon can be found in some meteorites (which he believed was probably of biological origin), he suggested that meteorites could be the carriers. If only one such organism fell on a planet suitable for life, it could become the starting point for Darwinian evolution.

Richter offered the ''elaboration in scientific terms'' in 1870: by assuming the existence of an atmosphere throughout empty space that would facilitate the transfer of life from planet to planet. Earth would leave a trail of polluted air containing germs and spores, which would occasionally fall through the atmospheres of other planets. When Richter made this outlandish proposition, he was in good intellectual company: that of many outstanding physicists who were proposing the existence of an ether as the universal medium for transmission of electromagnetic waves (Richter, 1870). Kamminga (1982) considered that Richter's incomplete theory had several commendable characteristics: in a nod to Pasteur it had removed spontaneous generation; it embraced Darwinism without having to explain the origin of life on a lifeless Earth; and it did not invoke supernatural agents.

Thus, it was that Richter set panspermia theory on a rational foundation for the first time. And that is what attracted Sir William Thomson (1824–1907) the most accomplished classical physicist of his time, who became known as Lord Kelvin, after Queen Victoria conferred a politically motivated peerage in 1892 to reward his opposition to Irish nationalism.

At the end of his very long Presidential Address to the British Association for the Advancement of Science (Edinburgh 1871), Sir William offered his support to the hypothesis that meteorites spawned panspermia:

> we all confidently believe that there are at present, and have been from time immemorial, many worlds of life besides our own, we must regard it as probable in the highest degree that there are countless seed-bearing meteoric stones moving about through space. If at the present instant no life existed upon this Earth, one such stone falling upon it might, by what we blindly call natural causes, lead to its becoming covered with vegetation.
> The hypothesis that [some] life [has actually] originated on this Earth through moss-grown fragments from the ruins of another world may seem wild and visionary; all I maintain is that it is not unscientific, [and cannot rightly be said to be improbable]. (Thomson, 1871/2011)

A few months later, German physicist Herman von Helmholtz (1821–1894) was at the podium in Heidelberg and Cologne, delivering public lectures on the Kant-Laplace nebular hypothesis of planetary formation. Helmholtz indicated that he had independently arrived at a similar hypothesis concerning meteorites somewhat earlier than Thomson (Helmholtz, 1874). Noting that meteorites sometimes contain carbon, and that the spectra of comets exhibit the spectra of gases containing hydrogen and carbon, he questioned,

> Carbon is the element, which is characteristic of organic compounds, from which living bodies are built up. Who knows whether these [meteorites and comets], which everywhere swarm through space, do not scatter germs of life wherever there is a new world, which has become capable of giving a dwelling place to organic bodies? (Helmholtz, 1871/1893)

This picture gained traction with biologists: in 1884, French biologist Philippe E.L. Van Tieghem (1839–1914) reported the novel concept in his comprehensive textbook on botany (Raulin-Cerceau *et al.*, 1998; Van Teighem, 1884). As we leave the 19th century, it is useful to remember that when Pasteur, Darwin, Richter, Thomson (Kelvin), and Helmholtz spoke of ''space'' and ''planets,'' their natural reference frame was the solar system rather than our Galaxy or the universe.

7. The 20th Century: Panspermia Becomes a Scientific Hypothesis

The physical sciences polymath Svante Arrhenius (1859–1927) recast panspermia as a thoroughly scientific hypothesis that could be developed rationally and subjected to falsifiability. He made it almost (but only almost …) a new field of science. Short biographies conventionally refer to Arrhenius as a chemist: he was, after all, awarded the third Nobel Prize for Chemistry in 1903 for his theoretical work on the conductivity of electrolytes (''Obituary, Prof. Svante Arrhenius,'' 1927). Once this research had gained general acceptance, he turned attention variously to atmospheric physics, astrophysics, and cosmogony—topics that formed the backbone of his definitive textbook *Lehrbuch der Kosmischen Physik* (Arrhenius, 1903). In chapter 4, entitled *Planets, moons and comets*, Arrhenius (1903) writes expansively on the possibilities for life elsewhere in the solar system.

> The large planets are plentiful with moons. These satellites have mostly cooled down so much that they have a solid surface … whose temperature would therefore be well below zero … if they were only dependent on the sun as a heat source. But the radiation of the [parent] planets, should not be inconsiderable. It would therefore be conceivable that these satellites could be partially suitable for the development of organic life.

More than a century later, Jupiter's icy satellite Europa is a prime target for astrobiologists. Its subsurface liquid water ocean and a composition likely to contain a suite of biogenic elements make it a compelling world in search for a second origin of life (Hand *et al.*, 2007). In 1907, Arrhenius published *Das Werden der Welten,* a popular and accessible account of his thoughts on the habitability of planets, and panspermia. The English language translation (1908) *Worlds in the Making: Evolution of the Universe* immediately introduced a global general readership to Arrhenius' ''conception that life is universally diffused, constantly emitted from all habitable worlds in the form of spores which traverse space for years or ages, the majority being ultimately destroyed by the heat of some blazing star, but some few finding a resting-place on bodies which have reached the habitable stage'' (Chisholm, 1910).

Paul Becquerel (1879–1955), an agronomist (and nephew of the famous physicist Henri Becquerel), rejected panspermia and experimented with ultraviolet radiation to test the viability of spores in outer space. His results were negative: spores and bacteria did not survive the ultraviolet radiation, and he did not believe they would tolerate the very low temperatures and a high vacuum. Therefore, life *must* be terrestrial in origin. On the other hand, he conceded that the biological conditions on early Earth *could* occur elsewhere, which led him to speculate on a ''universal cosmic hypothesis'' (Becquerel, 1910).

From the mid-1920s, the popularity of panspermia declined almost to invisibility. Its philosophical shortcomings such as the eternity of life, as well as epistemological objections, caused this neglect. More importantly, however, were developments in the theory of chemical evolution of the origin of life on Earth, which became a very lively area of research. It was becoming obvious that attempts to understand the origin of life needed an interdisciplinary approach.

In 1924, the Soviet biochemist Aleksandr Ivanovich Oparin (1894–1980) came to the conclusion that there is no fundamental difference between a living organism and lifeless matter. Life could perhaps have arisen from inorganic matter, and then self-assembled into primitive organisms:

> A whole army of biologists is studying the structure and organization of living matter, while a no less number of physicists and chemists are daily revealing to us new properties of dead things. Like two parties of workers boring from the two opposite ends of a tunnel, they are working towards the same goal. The work has already gone a long way and very, very soon the last barriers between the living and the dead will crumble under the attack of patient and powerful scientific thought. (Oparin, 1924/2020)

Oparin's *The Origin of Life,* published by the Academy of Sciences of the Soviet Union in 1936, argued that the conditions on early Earth might have enabled the synthesis of amino acids, which could subsequently self-assemble, subject to a suitable source of energy (lightning, geothermal, …), into the complex building blocks of life (Oparin, 1938). When published in English in 1938, Oparin's ideas attracted a global following: his was the first book to plausibly explain to a general readership how life could have begun (Farley, 1977).

Unfortunately, he later came to be neglected by the science community, particularly in the United States. This was partly a consequence of the isolation of Soviet science during the Cold War, as well as Oparin's reluctant support of the discredited Soviet pseudoscientist Trofim D. Lysenko (1898–1976) (Miller *et al.*, 1997). However, Oparin is respectfully remembered today by historians as the pioneer who gave momentum to the movement for understanding early molecular evolution (Brangwynne and Hyman, 2012).

The British biochemist John B.S. Haldane (1892–1964) independently offered a scenario for the natural emergence of life, claiming like Oparin that abundant synthesis of organic compounds was the necessary first stage for the origin of life on Earth (Haldane, 1929). Both were the first to set out the hypothetical geophysical conditions of the primordial environment and atmosphere, which were necessary for organic synthesis. Oparin backed up his arguments with circumstantial evidence from astrophysics, geosciences, and biochemistry.

His big leap in thinking was his program of exploration, through which he suggested that organic synthesis could have occurred *before* the emergence of organisms, and that this theory could be developed as new knowledge emerged in biochemistry and molecular biology (Fry, 2006). Panspermia meanwhile languished, an irrelevant distraction to research on the origin of life. Oparin continued his work on organic synthesis, with further publications on the origin of life in 1957 and 1968 (Oparin, 1968; Oparin, 1957).

8. Stanley Miller: Organic Synthesis Experiments 1952

When Stanley L. Miller (1930–2007), a first-year graduate student at the University of Chicago, attended a seminar in the Chemistry Department in 1951 given by Nobel Laureate Harold B. Urey (1893–1981), he became captivated by Urey's ideas on the origin of the solar system. Urey described the atmosphere of primordial Earth as likely consisting of an electrified highly reducing gas: methane, ammonia, hydrogen sulfide, and hydrogen. He surmised that within such an atmosphere, extensive electrical discharges would spark the synthesis of organic compounds, producing the raw materials for the emergence of life (Bada and Lazcano, 2012). At the time, Miller was being supervised by Edward Teller (1908–2003) on one of the hottest topics in cosmology: the origin of the chemical elements in the big-bang universe (Gamow, 1938).

However, he was making little progress and became dismayed when Teller abruptly departed Chicago for California to work on nuclear weapons at the new Lawrence Livermore National Laboratory. Desperately in need of a new thesis topic, Miller asked Urey if he could test Oparin's theory by running experiments on prebiotic synthesis in a reducing gas mixture. Initially, Urey resisted this risky request because Miller had nothing to show for his first year of research, and Oparin's theory seemed little more than intriguing table talk. He counseled his doctoral student to undertake experiments that had a reasonable chance of success. Even so, Miller persisted until Urey gave his consent, and when he did so, they designed and assembled the experimental setup together (Lazcano and Bada, 2008).

Within 2 days of sparking the gaseous mixture, Miller demonstrated the presence of glycine—the simplest stable amino acid, $C_2H_5NO_2$. After repeating the experiment for a week Miller noticed that the interior of the sparking flask was coated with a dark, oily material and the water had a yellow-brown tint. Further two amino acids were definitively detected by paper chromatography, together with weak indications of a handful more. When Urey reviewed the results, he set Miller to work immediately on a short article, which was submitted to *Science* on February 10, 1953. Urey declined Miller's offer of co-authorship, fearing that the addition of his name would deprive Miller of full recognition (Miller, 1953).

Following publication in *Science* on May 15, Miller carried out a more rigorous analysis that positively identified nine amino acids (Miller, 1955). First reports from repetition of Miller's experiments appeared 2 years later: they showed that significant prebiotic synthesis of amino acids required a spark discharge *and* a reducing gas (Hough and Rogers, 1956). These discoveries confirming Oparin's theory made headlines in major newspapers and magazines worldwide, grabbing the attention of public and professionals alike. Miller's demonstration that prebiotic synthesis may have occurred in the atmosphere of early Earth rejuvenated interest in panspermia: it blossomed overnight after lying fallow for half a century.

Although Darwin had set the scene for the explanation of biological processes within the framework of natural law, he had made no attempt in *The Origin of Species* to account for the emergence of primordial organisms on a lifeless Earth. Miller and Urey (1959) reviewed the numerous investigations that had been carried out ''with respect to the early chemical history of, and the synthesis of organic compounds, on the primitive earth.'' Their final paragraph prefigures the extent to which origin of life research was all about life in our solar system, rather than dreamy panspermic hypotheses:

> Surely one of the most marvelous feats of 20th-century science would be the firm proof that life exists on another planet. All the projected space flights and the high costs of such developments would be fully justified if they were able to establish the existence of life on either Mars or Venus. In that case, the thesis that life develops spontaneously when the conditions are favorable would be far more firmly established, and our whole view of the problem of the origin of life would be confirmed. (Miller and Urey, 1959)

9. Meteorite Theories in the Space Age

Three scientists with no prior experience of research on meteorites made an astonishing announcement in 1961: they had discovered biogenic hydrocarbons in a sample of the Orgueil meteorite in the collections of the American Museum of Natural History, New York. Specifically, they asserted that hydrocarbons in the meteorite resembled ''… hydrocarbons in the products of living things and sediments on Earth … the Orgueil meteorite provide[s] evidence for biogenic activity'' (Mitton, 2021; Nagy *et al.*, 1961). These declarations created popular interest worldwide, with one report including ''the first image of an extraterrestrial being.'' Such preposterous claims stimulated an expert team of meteoriticists at the University of Chicago, led by chemist Edward Anders, to scrutinize the friable meteorite.

They confirmed the presence of ''organized elements,'' but they amounted to nothing more than grains of magnetite (Fe_3O_4) plus terrestrial contaminants such as coal fragments, remains of plants typically found in southern France, and traces of animal glue (Fitch *et al.*, 1962)! They had uncovered a hoax perpetrated back in the 1860s: seed particles and pollen grains had been glued onto the meteorite (Anders *et al.*, 1964). Their forensic findings were critically important because the exaggerated claims were sowing doubt on the reality of extraterrestrial life.

Anders was one of many principal investigators who studied lunar samples brought back by the *Apollo* program. Two months after the *Apollo 11* landing, a bright orange fireball exploded near the small hamlet of Murchison in Victoria, Australia. The local residents duly gathered 100 kg of meteorite fragments strewn over the rural orchards, vineyards, and dairy farms. Two-thirds of the fragments of this carbonaceous chondrite went to the United States, where several laboratories were already prepared for the lunar samples from *Apollo 11*.

A team at the NASA Ames Research Center, California, found convincing evidence of amino acids of extraterrestrial origin in the Murchison meteorite. Half a century later, the tally of identified amino acids and bases exceeds 100. By the 21st century, the research interface between meteoritics and the origin of life in the solar system had become a thrilling area of astrobiology. Here is one version of that story:

> All known life is based on organic compounds and water and both of these have been present in the carbonaceous chondrites. As a result, these meteorites constitute a valuable ''natural laboratory'' of prebiotic chemical evolution. Analyses of the organic matter in meteorites can provide an inventory of the types of chemical reactions and organic products which could have been significant on the prebiotic Earth. This inventory substitutes our terrestrial record which has been obliterated by biological and geological activity. (Sephton, 2002)

Urey explained the chemical composition and structure of meteorites by proposing a two-stage process: the formation of objects of lunar and asteroidal size in the early solar system, followed by subsequent grinding to meteoritic fragments by collisional processes (Urey, 1956). He felt ''it is well to study objects that arrive from extraterrestrial sources quite without any effort or expense on our part.'' Urey co-organized a Symposium on the Exploration of Space hosted at the National Academy of Sciences, April 29–30, 1959 (Jastrow, 1959). From a detailed analysis of the ages and compositions of 42 meteorites, Urey reached the conclusion that they were likely of lunar origin, ''removed from the moon by some process such as collisions of iron meteorites or comet heads with the moon's surface'' (Urey, 1959).

In October 1961, Urey explored possible extraterrestrial origins of ''life-forms'' supposedly found in carbonaceous chondrites. On the balance of evidence, he concluded that there were ''good reasons for exploring possible origins of life-like forms in the carbonaceous chondrites, other than contamination … .'' In a leap of imagination that reads like the night thoughts of a crank, he speculated ''the Moon became contaminated temporarily with water and life-forms from Earth early in its history, that these forms have been preserved there and that they are now returning to Earth'' (Urey, 1962). He was more careful the following year when he summarized the articles presented at a New York Academy of Sciences gathering on hydrocarbon compounds in meteorites, urging that ''microbiologists, micropaleontologists, mineralogists, geochemists, and any other scientists …'' should be encouraged to join a serious study of the issues.

By 1965, further evidence from cosmic-ray ages and contaminants convinced Urey that meteorites of the Orgueil type came from the Moon and not the asteroid belt. In an aside, he touched on the negative implications for panspermia of a lunar origin of prebiotic organics. However, critics railed against this ''highly speculative,'' ''poorly focussed effort'' that was ''insufficiently supported'' (Hayes, 1967; Ringwood, 1966; Ringwood, 1965).

10. Directed Panspermia 1970s: The View from Cambridge, United Kingdom

The concept that technologically advanced extraterrestrial civilizations could have seeded life on Earth gained prominence in the 20th century, after humans had mastered heavier than air flight, rocket propulsion, and the exploration of space by probes and landers (Ginsburg and Lingam, 2021). Some writers credit the science fiction author Stapledon (1930) with the first mention of ''disseminating among the stars the seeds of a new humanity'' by launching immense quantities of such seeds that would propagate throughout the Galaxy, propelled by solar radiation. The first mention in the *scientific* literature was by Shklovskii and Sagan (1966).

During the 1960s, the research of Francis H.C. Crick (1916–2004), a theoretical microbiologist at Cambridge, targeted the origins of the genetic code. Crick, James D. Watson (b. 1928), and Maurice Wilkins (1916–2004) shared the 1962 Nobel Prize in Physiology or Medicine for ''their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material''—thereby unlocking the key of life (Watson and Crick, 1953). Crick had a lifelong interest in how molecules could make the transition from nonliving to living matter, a quest that attracted him to panspermia. During summer of 1972, a few months after Crick and his colleague Leslie Orgel (1927–2007) had attended a meeting on Communication with Extraterrestrial Intelligence held at the Byurakan Observatory, Armenia, they composed the foundational article on directed panspermia (Crick and Orgel, 1973).

The reader can clearly see the various influences of Oparin, astrophysicist Thomas (Tommy) Gold (1920–2004), theoretical physicist Freeman Dyson (1923–2020), and planetary scientist Carl Sagan (1934–1996). Crick and Orgel advanced a highly specific version of directed panspermia: deliberate transfer (''infection'') of microorganisms sent ''by a technological society on another planet, by means of a special long-range unmanned spaceship!'' They firmly rejected the 19th century suggestions that life could have arrived on Earth as spores propelled by stellar radiation pressure or as living organisms embedded in a meteorite.

Crick and Orgel benefitted from the earlier research of microbiologist Peter H.A. Sneath (1923–2011) on the longevity of bacterial spores (Sneath, 1962). Sneath had considered that ''life could probably be preserved for periods of more than a million years, if suitably protected and maintained at temperatures close to absolute zero.'' Furthermore, he had advocated the following: ''[the] panspermic hypothesis that life has spread throughout the universe'' should not be discarded lightly. Picking up on that thread, Crick and Orgel conjectured that it was not totally implausible for bacterial spores to survive for several million years.

This tentative proposition went further than those of Sagan and Sneath, because they suggested that present-day organisms should be carefully scrutinized to see if they carried any vestigial trace of extraterrestrial origin, given the uniformity of the genetic code across all terrestrial life forms. In a flight of fancy, they questioned if descendants of extraterrestrial life are still alive? Life on other planetary systems may have made many attempts to infect the galaxy, perhaps implying ''we have cousins on planets which are not too distant.'' Except, … except, … ''Perhaps our galaxy is lifeless except for a local village of which we are one member.''

11. Fred Hoyle, Chandra Wickramasinghe, and Panspermia

When Watson and Crick published their celebrated article in 1953, they were at the University of Cambridge, as members of a UK Medical Research Council research unit for molecular biology based at the Cavendish Laboratory. Jim was a graduate student at Clare College and Francis was a former doctoral student of Gonville and Caius College. Fred Hoyle, the noted cosmologist and controversialist, was elected in 1939 to a research fellowship at St John's College, a position to which he returned after war work. In the late 1940s and early 1950s, Cambridge colleges provided an ideal environment for men of science such as Crick, Hoyle, Watson, and world-class early career academics to mingle freely, playing as chums who bounced ideas off each other.*

Hoyle appreciated the company of Crick and Watson, and like them, he became fascinated by the origin of life, evolution, and adaptation, and the nature of human consciousness. His first work of fiction *The Black Cloud* is about a cloud of gas and dust that enters the solar system, causing drastic climate change. The bizarre behavior of this alien Cloud baffles the boffins advising the government. The scientists come to the conclusion that it is a gaseous super organism. When the Cloud realises there are intelligent lifeforms on Earth, it reconfigures. And Earth is spared.

In 1948, Hoyle had made this startling prediction in a radio broadcast:

> Once a photograph of the Earth, taken from outside, is available … a new idea as powerful as any in history will be let loose. (Hoyle, 1950)

He later looked back with great pleasure on this forecast: in a speech before the First Lunar Science Conference in Houston, Texas, he proclaimed the following:

> Well, we now have such a photograph. I've been wondering how this old prediction stands up. Has any new idea in fact been let loose? It certainly has … everybody has become seriously concerned to protect the natural environment. Something unique has happened to create an awareness of our planet as a unique and precious place. (Hoyle, 1970)

Something unique had happened. By the 1970s, we were envisioning missions to search for signs of life in the solar systems. Recall that the *Viking* landers (1976) conducted three microbiology experiments to search for signs of life on Mars.

Fred Hoyle had formulated his steady-state version of cosmology in 1948, but by 1965, this theory of an everlasting expanding universe fell out favor following the serendipitous discovery of the cosmic microwave background radiation, a fossil relic of the Big Bang. Hoyle founded the prestigious Institute of Theoretical Astronomy (IOTA) at

*Note to readers: Girton College and Newnham College on the outskirts of the city were the only foundations admitting women to the University of Cambridge. Women were not awarded their degrees until 1948.

Cambridge in 1965. Seven years later, when the University of Cambridge merged IOTA with the Cambridge Observatories and declined to appoint him director, Hoyle impetuously resigned his professorship. He no longer had a salaried faculty position in a major university, and had to live by his wits—his intellect and resourcefulness (Mitton, 2011).

Simon Mitton (author of this article) was a research fellow at the Institute when Hoyle left. He recalls that, research in Cambridge remained vibrant, intense, stimulating, and highly creative, despite Hoyle's exit. Former colleagues were often surprised by the direction that Hoyle's research took in his twilight years, particularly his abrupt switch from cosmology to panspermia. That is when Hoyle began to collaborate with his former doctoral student Professor Chandra Wickramasinghe of Cardiff University (Gregory, 2005).

Hoyle and Wickramasinghe shared an interest in dense interstellar clouds. By the early 1970s, such clouds were already known to harbor abundant supplies of the simpler organic molecules. In collegiate Cambridge, Hoyle had many opportunities to interact with the pioneers of molecular biology: he was on first-name terms with half a dozen laboratory molecular biologists who became Nobel laurates. Fred and Chandra visualized that biochemistry could have originated among the prebiotic molecules and grains in molecular clouds, ultimately leading to the formation of bacterial clumps on the surfaces of dust grains.

To counter the objection that bacteria are easily destroyed by ultraviolet radiation, they presumed dense molecular clouds harbored billions of comets, the by-product of the condensation of volatile matter during the formation of the solar system. Maybe bacteria could survive interstellar transfer by hiding inside comets; and perhaps the larger comets would have warm liquid interiors where the assembly of molecules into primitive living cells could take place (Hoyle and Wickramasinghe, 1978)? The earliest phase of biological evolution could thus have occurred not in space or on Earth, but in cometary interiors. We know that in the first billion years, the moons and planets of our solar system were assailed by severe cometary bombardment.

Planetary scientists were suggesting that incoming comets had brought abundant water to Earth. Hoyle and Wickramasinghe (2000) extended this cometary water wagon idea, with their proposal that comets had carried microorganisms to Earth about 4 billion years ago. Their boldest move was a proposition that life in space had progressed as far as bacteria, the most prevalent life-form on Earth. Evolutionary biologists working on the origin of life consider that accounting for the steps from simple molecules to bacteria is a more difficult task than explaining the several steps from bacteria to humans. That is one of the reasons why Hoyle–Wickramasinghe panspermia has never been taken seriously by molecular biologists. The astronomical community also viewed the hypothesis with skepticism bordering on scorn—it made no sense.

What really upset the biologists, although, were Hoyle and Wickramasinghe's claims that major epidemics and pandemics were triggered by the seeding of the atmosphere with viruses expelled from passing comets. They did not expect this quirky hypothesis to be accepted by a scientific journal, so they wrote a popular book, *Diseases from Space*, which gave their argument and its supporting research (Hoyle and Wickramasinghe, 1979). The attendance registers of several UK boarding schools provided the data for their investigation on the cause of the 1978 influenza epidemic in England and Wales.

From their analysis, they concluded that epidemics were seeded by the vertical transfer from the stratosphere to the surface pathogenic of cometary microorganisms (Hoyle and Wickramasinghe, 1982). The sudden appearance of completely new pathogens, such as Legionnaires' disease in 1976, only added to their conviction that nasty bugs came from space. Media interviews gave them plenty of opportunities to publicize their opinions.

The Hoyle–Wickramasinghe collaboration became productive on 1 metric: about 20 articles published in peer-reviewed journals and several popular books. They embraced the public arena, giving many interviews for broadcast and print media. Both were accomplished public outreach activists at promoting their own point of view. Their professional colleagues, however, were always less supportive, being unconvinced by large claims supported by slender evidence. For example, their analysis of sparse data on Legionnaires' disease in 1976 and the influenza epidemic in 1978 had lacked any engagement with distinguished virologists and epidemiologists (Mitton, 2005). On another metric, the sheer volume of articles, the frequency with which they appeared, and their low citation rates contributed a general feeling that the oeuvre did not meet the academic standards expected by the community. Professionals felt that long-established standards of the scientific method of enquiry were not being respected.

Today, the Hoyle-Wickramasinghe articles seem like a swansong for the period spanning the 18th, 19th, and 20th centuries, during which application of the scientific method assumed much greater importance when addressing the conjectures of panspermia. By the late 1970s, the spectacular growth of planetary exploration meant that real data could be used (or at least anticipated), which would constrain, and thus strengthen, the panspermia concept. The transition from conjecture to a testable and falsifiable science was complete. From the late 1980s, the possibility that life could diffuse through the solar system by interplanetary panspermia was discussed widely, in particular, panspermia operating between Earth and Mars (Melosh, 1988).

The next leap in interest was driven by discoveries of exoplanets ($\sim$5000), including multiple planet systems ($\sim$900) with a terrestrial planet or Super Earth (Exoplanet Catalog, 2022). Many articles use data on multiple systems to estimate the probability of panspermia occurring in multiple systems. A simple model of lithopanspermia (transfer of life by rocks) applied to the seven planets in the TRAPPIST-1 system shows that the likelihood of this occurring is orders of magnitude higher than Earth-to-Mars transfer (Lingam and Loeb, 2017). However, one can ask if this modeling of *interplanetary* lithopanspermia can be extended over the entire phase space to *intragalactic* transfer? Ginsburg *et al.*, (2018) have found that the parameter space for lithopanspermia extends beyond the scale of planetary systems. Natural exchange of biotic components across vast distances—the entire Milky Way—cannot be dismissed (Ginsburg *et al.*, 2018).

12. ‘Oumuamua, an Enigmatic Interstellar Intruder Enlivens the Debate

On October 19, 2017, the Pan-STARRS telescope at the Haleakalā Observatory Hawaii detected a small red oblong object a few 100 m in size travelling at an excessive velocity (Meech *et al.*, 2017). It was named ‘Oumuamua and within a few weeks, astronomers had deduced from its orbit that it was an interstellar object. Opinions were expressed that it might be an errant asteroid from another solar system or a feeble fragment of a fractured comet. Unsurprisingly, there were those who speculated that it could an artifact from an alien civilization, although such hypotheses were soon dismissed as infeasible.

In March 2021, Jonathan Katz of Washington University (St Louis, Missouri) summarized the evidence against the concept that an alien civilization had launched artifact and raised it to semirelativistic speed by laser acceleration as ‘‘not credible’’ (Katz, 2021). Be that as it may, the discovery of ‘Oumuamua, followed by detection of a second such interstellar object, served to put panspermia and alien civilizations back in the spotlight for 3 or 4 years. It is an intriguing event, with which to conclude this short history of panspermia.

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IOTA = Institute of Theoretical Astronomy