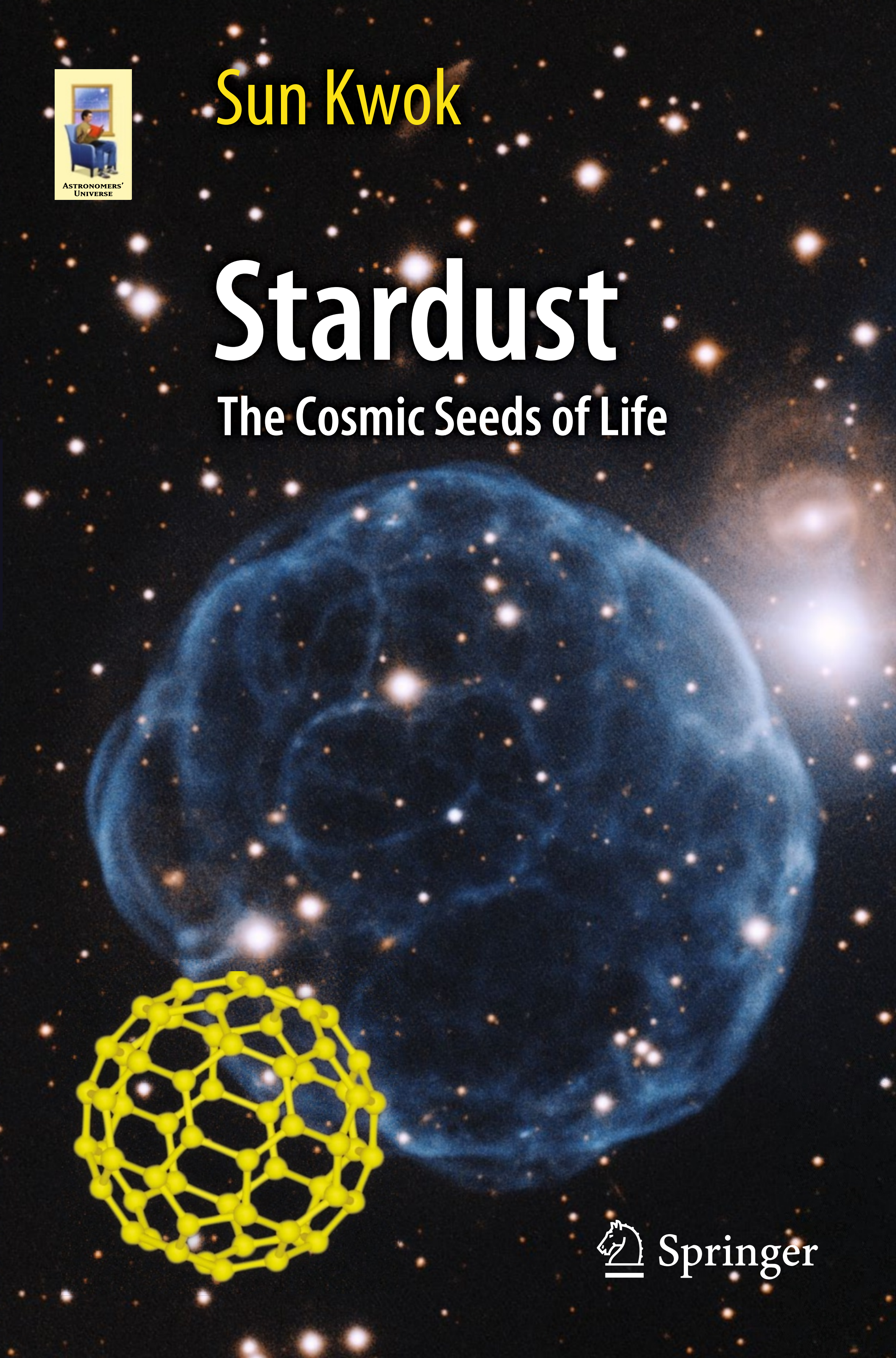
Astronomers' Universe

Sun Kwok

Stardust

The Cosmic Seeds of Life



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Sun Kwok
The University of Hong Kong
Faculty of Science
Hong Kong
China, People's Republic

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Preface

When I was in my second year of undergraduate studies, I read a book by Fred Hoyle called "*Frontiers of Astronomy*". Before reading this book, I had an idea that astronomy involved observing the skies and monitoring celestial events. From Hoyle's book, I realized that modern astronomy is much more than just observations. It is about applying our knowledge of physics to understand the Universe. As a result, I changed my major from engineering to physics with the goal of becoming an astronomer. As a graduate student at the University of Minnesota, I had the good fortune to witness the beginning of infrared spectroscopy. The mid-infrared detectors developed at Minnesota allowed the exploration of the sky in the infrared, and the unexpected discovery of infrared emissions from old stars led to the first positive identification of a mineral in stardust - silicates.

This book is about 40 years of history of the search for an understanding of the nature of stardust. No one predicted the existence of organic stardust, and certainly no one foresaw the wide spread of organic matter in the Universe. This is a fascinating story that ought to be told.

In the early 1990s I began writing a series of popular articles for the *Sky and Telescope*, *Astronomy*, and *Mercury* magazines. These writings got me interested in writing about science for the general public. This led to my first popular science book *Cosmic Butterflies* published by Cambridge University Press in 2001. The subsequent book tours and invitations to speak in USA and Canada allowed me to meet face to face with many of the readers. The strong interest and thirst for information by the public have convinced me of the need for the communication of the latest scientific results in an authoritative but understandable manner.

When we read about significant discoveries of the past, we often don't appreciate how difficult the path has been. Accounts are often sanitized and simplified. But the reality of science is that success occurs after many errors, detours, and dead ends and is never straightforward. My own participation in the research on this subject has also allowed me to witness first-hand how things happened and I hope to relay these events in this book.

Since science is a human endeavor, personalities are an integral part of the process. In this book, I benefited from the personal accounts of many people involved in the research on stardust, in particular those who related to me their personal experiences on the road to discovery.

Unlike most popular science books, this book is more than a report of discoveries. Through the reading of the primary literature and personal interactions with the scientists who do the work, I was able to evaluate the evidence, form my own critical assessment of the work, and determine how it fit into the overall picture of the development of the field.

On the personal side, I am grateful to NASA and ESA who allowed me access to their telescopes through the policy of open competition for telescope time. Without this generous policy, it would not have been possible for me to contribute to this field.

Both astrochemistry and bioastronomy are new scientific disciplines. My service as a member of the executive committees in the International Astronomical Union astrochemistry and bioastronomy commissions gave me the opportunity to meet other scientists in the field and to promote these two subjects in the general scientific community. This book gives me a way to "wave the flag" and hopefully encourage more young people to pursue research in these areas.

I started the earliest draft of this book more than 10 years ago. Due to my administrative duties, I have only been able to write in bits and pieces of spare time that I can find. I want to thank the people and organizations in different parts of the world who have invited me to give talks on the subject of stardust, which gave me confidence that this subject is indeed of wide public interest.

I want to thank Agnes Lam who kindly gave permission to me to include her beautiful poem in this book, as well as giving valuable comments on an earlier draft of the book. I would like to thank my editor Ramon Khanna of Springer who took an interest in this project. I would also like to express my gratitude to Arturo Manchado for his hospitality during my stay at the Instituto de Astrofisica de Canarias. Anisia Tang, my friend and colleague, helped in the production of some of the drawings used in this book. I want to thank my wife, Emily, and my daughter, Roberta who have read various drafts of this book and gave me valuable feedback and comments.

Hong Kong, Sun Kwok
People's Republic of China
December 2012

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Prologue

The Heaven and Earth connection is one of the oldest concepts of mankind. All the ancient cultures subscribed to the belief that our lives are guided and governed by celestial objects. Astrology is just one example of such beliefs. However, with the growth of technology, our connections to the heavens have diminished. With artificial lighting, we are less dependent on the rise and setting of the Sun. The role of the Moon as an illumination source at night is all but forgotten. An increasing number of people live in cities where light pollution makes it difficult for residents to see and appreciate the stars. The passing of comets is something we read in the news, but not the first-hand visual spectacle that awed the citizens of the past.

In modern times, the intellectual community has come to believe that we originated and developed from this Earth. Life began, evolved, and prospered on this planet, in total isolation from the rest of the Universe. Stars are remote, distant, and irrelevant entities. It is in this context and background that I am writing this book, to remind us that stars have been a major part of our origin. We can be oblivious to their birth, life, and death, but it is quite likely that these distant objects were responsible for our existence. If someone were to say this 30 years ago, the idea would have been dismissed out of hand. But lots of things have changed. The development of space and astronomical technology has brought us unprecedented capabilities to study stars. The discovery of stardust, in particular that made up of organics, was totally unexpected and still difficult to understand. In spite of our lack of theoretical understanding, the observational facts are clear and definite. Stars, near the end of their lives, are able to synthesize extremely complex organic compounds under near vacuum conditions. Large quantities of organics are manufactured over very short time scales, and ejected and distributed throughout the Galaxy. With space spectroscopic observations, we can determine the chemical composition of these stardust particles, and surprisingly, we found them to show remarkable resemblance to the organic solids in meteorites. Since meteorites are remnants of primordial solar nebula, is it possible that stars have enriched our Solar System with organics? This idea has gained support from the discovery of pre-solar grains, inorganic stellar grains that have been demonstrated to have come from old stars outside of the Solar System. Recent research has also told us that the Earth was subjected to heavy bombardments from comets and asteroids during the early history of the Earth. These bombardments may have brought with them the primordial organics, seeding the Earth with raw materials as basic ingredients of life.

This scenario was developed as the result of the work of many people. There are astronomers who perform observations of distant stars, laboratory chemists who identify the spectral signatures of organics, space scientists who send probes to comets, asteroids, and planetary satellites, meteoritic scientists who examine the chemical composition of meteorites and interplanetary dust particles, geologists who study the early history of the Earth, and biologists who weave a picture of how life could originate from these distant organics. It has been a very exciting experience for me to have been a part of these teams. Sometimes these discoveries seem too fantastic to be true and there has not been a lack of skeptics in the scientific community.

The question of the origin of life is such a complicated issue that the complete answer may not be secured in the near future. But what we have learned is that we have to keep an open mind for unexpected discoveries and entertain new possibilities resulting from these new findings. What I am certain of is that the final answer will not be arrived at by a scientist from a single discipline, but by teams of scientists attacking the problem from a variety of angles, each bringing a piece of the puzzle that hopefully can be put together to form a picture.

This book is about stardust, the smoke from stellar chimneys. We tell the story of how it was discovered, what it is made of, and what effects it may have on the Solar System and the origin of life.

About the Author

Sun Kwok is a leading world authority on the subject of astrochemistry and stellar evolution. He is best known for his theory on the origin of planetary nebulae and the death of Sun-like stars. His recent research has been on the topic of the synthesis of complex organic compounds in the late stages of stellar evolution. He is the author of many books, including *The Origin and Evolution of Planetary Nebulae* (2000), *Cosmic Butterflies* (2001), *Physics and Chemistry of the Interstellar Medium* (2007), and *Organic Matter in the Universe* (2012). He has been a guest observer on many space missions, including the *Hubble Space Telescope* and the *Infrared Space Observatory*. He currently serves as the President of Commission 34 interstellar Matter of the International Astronomical Union (IAU), as well as Vice President of IAU Commission 51 Bioastronomy. He served as the chairman of IAU Planetary Nebulae Working Group between 1994 and 2001, and as organizing committee member of IAU Astrochemistry Working Group.

Vanilla in the Stars

By Agnes Lam
Special Mention Award, 24th Nosside International Poetry Prize

When I was a child,
I used to gaze at the stars above

our garden of roses, jasmine and *lingzhi* by the sea,
wondering how far away they really were,
whether they were shining still at the source
by the time their light reached me . . .

I was told that everyone was born with a star
which glowed or dimmed with the fortunes of each.
I also heard people destined to be close
were at first fragments of the same star

and from birth went searching for each other.
Such parting, seeking, reuniting might take
three lifetimes with centuries in between.
I had thought all these were but myths . . .

Now decades later, I read about the life of stars,
how their cores burn for ten billion years,
how towards the end, just before oblivion,
they atomize into nebulae of fragile brilliance –

ultra violet, infra red, luminous white, neon green or blue,
astronomical butterflies of gaseous light
afloat in a last waltz choreographed by relativity,
scattering their heated ashes into the void of the universe . . .

Some of this cosmic dust falls onto our little earth
carrying hydrocarbon compounds, organic matter
able to mutate into plant and animal life,
a spectrum of elemental fragrances . . .

Perhaps on the dust emanating from one ancient star
were borne the first molecules of a *pandan* leaf,
a sprig of mint or basil, a vanilla pod, a vine tomato,
a morning frangipani, an evening rose, a lily of the night . . .

Perhaps our parents or grandparents or ancestors further back
strolling through a garden or a field had breathed in the scents
effusing from some of these plants born of the same star
and passed them on as DNA in the genes of which we were made . . .

Could that be why, on our early encounters, we already sensed
in each other a whiff of something familiar, why when we are near,
there is in the air some spark which seems to have always been there,
prompting us to connect our pasts, share our stories even as they evolve . . .

. . . till the day when we too burn away into dust
and the aromas of our essence dissipate
into the same kaleidoscope of ether light
to be drawn into solar space by astral winds . . .

. . . perhaps to make vanilla in a star to be
before the next lifetime of three?

Chapter 1
Where Do We Come From?

How did life originate on Earth? Was it the result of supernatural creation? Or are we the product of deliberate planting by advanced extraterrestrial civilizations? If life is the result of divine intervention, did life appear suddenly with all its functions and capabilities, or had the diverse forms of life on Earth developed over time from certain holy seeds? If extraterrestrials are involved, are we a duplicate of their forms, or were we created as an experiment? If so, did they actually visit Earth or did they deliver their experimental ingredients programmed with specific instructions to this planet by a space probe? Alternatively, maybe we were products of accidental developments, arising naturally without design. If so, what was the initial mix of ingredients? How complicated were the ingredients? How did these ingredients get to the surface of Earth? Were they present when the primordial Earth was formed, or could they have been brought here after the formation of Earth? Could these externally delivered ingredients include primitive life forms such as bacteria?

These are very ambitious questions which until recently would have been regarded as outside the realms of science. However, from the 1970s, we have witnessed the emergence of new scientific disciplines of astrochemistry and astrobiology. These new disciplines have opened new avenues to tackle the old question of the origin of life. Instead of speculation, conjecture, or faith, we can now attempt to answer this question in a scientific manner.

The oldest hypothesis, and also the most common among all cultures, is that life is the result of supernatural intervention. Most primitive cultures believe that they owe their existence to a supreme being. This theory, in its most general form, is impossible to refute by scientific method although specific theories with definite descriptions of sequence of events and the nature of the creation can be subjected to scientific tests.

Our Solar System resides in the Milky Way Galaxy, which has over 100 billion stars, many similar to our own Sun. The Universe as a whole has more than 100 billion galaxies similar to the Milky Way. The age of our Galaxy is estimated to be about 10 billion years old, and the Universe is only slightly older (currently believed to be about 14 billion years). Recent advances in planet detection

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techniques have revealed over 700 planets around nearby stars. It is quite likely that planetary systems are extremely common around Sun-like stars. If we extrapolate the planet detection rate to distant stars, then the number of planets in our Galaxy could also run into hundreds of billions. Of course, we don't know what fraction of these planets harbors life as the Earth is the only place we know to possess life. But if life forms do exist elsewhere, then many would be inhabiting planets around stars that have been around much longer. Their civilizations would be millions, or even billions of years older than ours. Given the fact that human civilization only started thousands of years ago, and our technological societies only began hundreds of years ago, it is extremely likely that there are many alien civilizations that are much, much more advanced than ours. If this is the case, then the chance is high that some of them would have visited us already.

However, even if extraterrestrial life forms had visited us we may not have recognized them. For example, if our young and relatively backward technological society had the ability to go back several hundred years to leave behind a DVD containing thousands of pictures and videos and music, our ancestors would not be able to see it as more than a piece of shining metal, nor would they be able to decipher its contents. An artifact left behind by an alien advanced civilization is likely far too elusive or mysterious for us to notice or to comprehend. If extraterrestrial intelligent beings had visited the Earth, they would not have left primitive objects such as the pyramids or simple marks on the ground. The absence of evidence for visits by extraterrestrials is therefore no proof of their not having done so. If we were indeed visited, either by advanced life forms or by robots they sent, they could have easily seeded life on Earth without our ever realizing it had happened.

It is clear that some hypotheses on the origin of life, although within the realm of possibility, are difficult or impossible to disprove. As scientists all we can do is to use our present knowledge of astronomy, physics, chemistry, and biology to investigate whether theories of the origin of life stand up to observational and experimental tests.

The hypothesis of spontaneous creation, which states that life arises from nonliving matter, has a long history. The Greeks, for example, promoted the theory that everything is created from primary substances such as earth, water, air, and fire. The idea that plants, worms, and insects can spontaneously emerge from mud and decaying meat was popular up to the seventeenth century. This theory was put to severe tests in the seventeenth century when the Italian physician Francesco Redi (1626–1698) noticed that maggots in meat come from eggs deposited by flies. When he covered the meat by a cloth, maggots never developed. This experiment therefore cast doubts on the premise that worms originate spontaneously from decaying meat.

The invention of the microscope has revealed the existence of large varieties of microorganisms which are invisible to the naked eye. A Dutchman, Antonie van Leeuwenhoek (1632–1723), found microorganisms in water and therefore showed that minute life is common. Van Leeuwenhoek was a tradesman who lived in Delft, Holland and had no formal training in science. He did have good skills in grinding lenses and made a large number of magnifying glasses for observations. He had put everything imaginable under his home-made microscope. The list of samples that he had observed include different sources of water, animal and plant tissues, minerals, fossils, tooth plaque, sperm, blood, etc. By using proper lighting during his observations, he was able to see things that no one had seen before. Among his many discoveries, the most notable is the discovery of bacteria, tiny living, moving organisms that are present in a variety of environments. For his achievements, this amateur scientist was elected as a member of the Royal Society in 1680.

Van Leeuwenhoek believed that these life forms originate from seeds or "germs" that are present everywhere. A revised form of spontaneous creation therefore contends that while large life forms such as animals may have come from eggs, small microscopic creatures can still be created from the non-living. This question was finally settled by Louis Pasteur (1822–1895) who showed that the emergence of microorganisms is due to contamination by air. His pioneering experiment is the beginning of our modern belief that life only comes from life on Earth today.

If this is the case, then when did the first life on Earth begin and how? By the late nineteenth century, scientists realized that the Earth is not thousands or millions, but billions of years old. Although life can no longer be created in the current terrestrial setting, may be it was possible a long time ago when the Earth's environment was very different. With suitable mixing of simple inorganic molecules in a primordial soup, placed in a hospitable environment and subjected to injection of energy from an external source, life may have originated over a long period of time. Given the old age of the Earth, time is no longer an issue. The idea that the origin of life on early Earth could be explained using only laws of physics and chemistry was promoted by Soviet biochemist Aleksandr Ivanovich Oparin (1894–1980) and British geneticist John Burdon Sanderson Haldane (1892–1964) in the 1920s.

Their ideas were motivated by the success of laboratory synthesis of organics in the nineteenth century. Historically, the term "organics" was used to refer to matter that is related to life, which is distinguished from "inorganic" matter such as rocks. It was assumed that inorganic matter can be synthesized from the basic elements (such as atoms), whereas organic matter possesses a special ingredient called the "vital force". The concept that the "living" is totally separated from the "non-living" was entrenched in ancient view of Nature. To draw an analogy, the concept of "vitality" separating living from nonliving is equivalent to the concept of "soul" which supposedly distinguishes humans from other animals. The concept of vitalism can be summarized in the words of the nineteenth century physician–chemist William Prout (1785–1850): "(there exists) in all living organized bodies some power or agency, whose operation is altogether different from the operation of the common agencies of matter, and on which the peculiarities of organized bodies depend". As for the form of this "power", he said "independent existing vital principles or 'agents,' superior to, and capable of controlling and directing, the forces operating in inorganic matters; on the presence and influence of which the phenomena of organization and of life depend". This was the prevailing view in the nineteenth century.

The concept of "vitality" originated from simple observations that living things can grow, change and move, whereas non-living things cannot. These activities are now explained by the modern concept of "energy", which explains movement as the conversion from one form of energy (chemical) to another (kinetic). In spite of the introduction of the concept of energy, "vital force" remained a popular concept in chemistry. However, the physical form of "vitality" was never precisely defined nor quantified, although by the nineteenth century, it was believed to be electrical in nature.[1] Nevertheless, "vital force" was thought to be real as it was the absence of "vital force" that was assumed to make it impossible to synthesize organics chemically from inorganics. In 1828, Friedrich Wöhler (1800–1882) synthesized urea, an organic compound isolated from urine, by heating an inorganic salt ammonium cyanate. This was followed by the laboratory synthesis of the amino acid alanine from a mixture of acetaldehyde, ammonia, and hydrogen cyanide by Adolph Strecker (1822–1871) in 1850, and the synthesis of sugars from formaldehyde by Aleksandr Mikhailovich Butlerov (1828–1886) in 1861. While it was thought that a vital force in living yeast cells is responsible for the process of changing sugar into alcohol, Eduard Büchner (1860–1917) showed in 1897 that yeast extracts can do the same without the benefit of living cells. The successes of these artificial syntheses led to the demise of the "vital force" concept.

The discipline of biochemistry emerged from this philosophical change. Biochemistry is based on the premise that biological forms and functions can be completely explained by chemical structures and reactions. The catalysts that accelerate chemical reactions in biological systems are biomolecules that we now call enzymes. In 1926, James Sumner found that an enzyme that catalyzes urea into carbon dioxide (CO_2) and ammonia (NH_3) belongs to the class of molecules called proteins. James Batcheller Sumner (1887–1955) had only one arm, having lost the other due to a hunting accident when he was a boy. When he tried to undertake Ph.D. research in chemistry at the Harvard Medical School, he was advised by the chairman of the biochemistry department that he should consider law school as "a one armed man could never make it in chemistry". However, he did finish his Ph.D. at Harvard and took up a position as assistant professor in the Department of Physiology and Biochemistry in the Ithaca Division of Cornell University Medical College. Although he had limited equipment or research support, he took on the ambitious project to isolate an enzyme. After 9 years, he crystallized the enzyme urease. His results were doubted by his contemporaries and his work was only fully accepted in 1946 when he was awarded the Nobel Prize.

Many other digestive enzymes also turned out to be proteins. The magic of life has therefore been reduced to rules of chemistry. By the early twentieth century, this has become the new religion in science. Living matter, although highly complex, is nothing but a large collection of molecules and the working of life is

[1] It is interesting that the quantification of "soul" can be found in modern popular culture. The 2003 movie "21 Grams" mentions the supposed scientific study showing that people lose 21 g in weight at the time of death, presumably due to the separation of soul from the body.

no more than a machine having numerous molecular components working with each other. Under such a belief, the origin of life could also be understood through a set of chemical reactions. These new laboratory developments therefore set the stage for the adaptation of the Oparin-Haldane hypothesis as the dominant theory of the origin of life by the mid-twentieth century.

Although the Oparin-Haldane hypothesis had a sound scientific basis, it was also politically convenient for Oparin because the idea of life originating from non-living matter fits in well with the Marxist philosophical ideology of dialectic materialism. Oparin graduated from Moscow University in 1917, right at the time of the Russian revolution. He began his research in plant physiology and rose to become the director of the Institute of Biochemistry of the USSR Academy of the Sciences in 1946. Beginning as early as 1924, he explored the idea that life could originate from simple ingredients in the primitive Earth. Oparin was very successful in the Soviet Union, becoming Hero of the Socialist Labor in 1969, recipient of the Lenin Prize in 1974, and five Orders of Lenin. It is interesting that Haldane, a British geneticist, was also a devout Marxist. He was a member of the communist party of Great Britain, although in his later years he broke away from Stalinism because the Soviet regime was persecuting scientists in the Soviet Union. In 1956, Haldene left his position at University College London and moved to India, as he disagreed with the British world political stand on the Suez Canal at that time. He became a vegetarian and wore Indian clothing. He died in India in 1964.

It is difficult to know whether the Marxist philosophical leanings of Oparin and Haldane had any bearings on their independently developed ideas on the origin of life, but it is probably fair to say that their theory had more in common with a mechanical view of the universe than a spiritual one, as was popular at the time. Oparin's work was not known in the west until the translation of his book "*The Origin of Life*" into English in 1938 and republication in the U.S. in 1952, and Haldane's ideas were dismissed as mere speculations. Haldane wrote many books, some of them popular ones, even some for children. The fact that he was a prolific and eloquent writer certainly helped to keep him in the public limelight; otherwise his work on the origin of life might have been forgotten.

The Oparin-Haldane hypothesis only gained respectability after the experimental demonstration in the 1950s. In a milestone experiment in 1953, Stanley Miller (1930–2007) and Harold Urey (1893–1981) of the University of Chicago showed that given a hospitable environment (e.g. oceans) and an energy source (e.g. lightning), complex organic molecules can be created naturally from a mixture of methane, hydrogen, water, and ammonia. Using a flask to simulate the primitive atmosphere and ocean and injecting energy into the flask by electric discharge, Stanley Miller found that a variety of organic compounds such as sugars and amino acids emerged in this solution. This experiment had an extraordinary impact on the thinking of the scientific community. For the first time, spontaneous creation seemed to be a possibility (Fig. 1.1).

Stanley Miller was a graduate student at the University of Chicago, originally working with the nuclear physicist Edward Teller. After Teller left Chicago, Miller had to find a new advisor and he approached the geochemist Harold Urey, who had