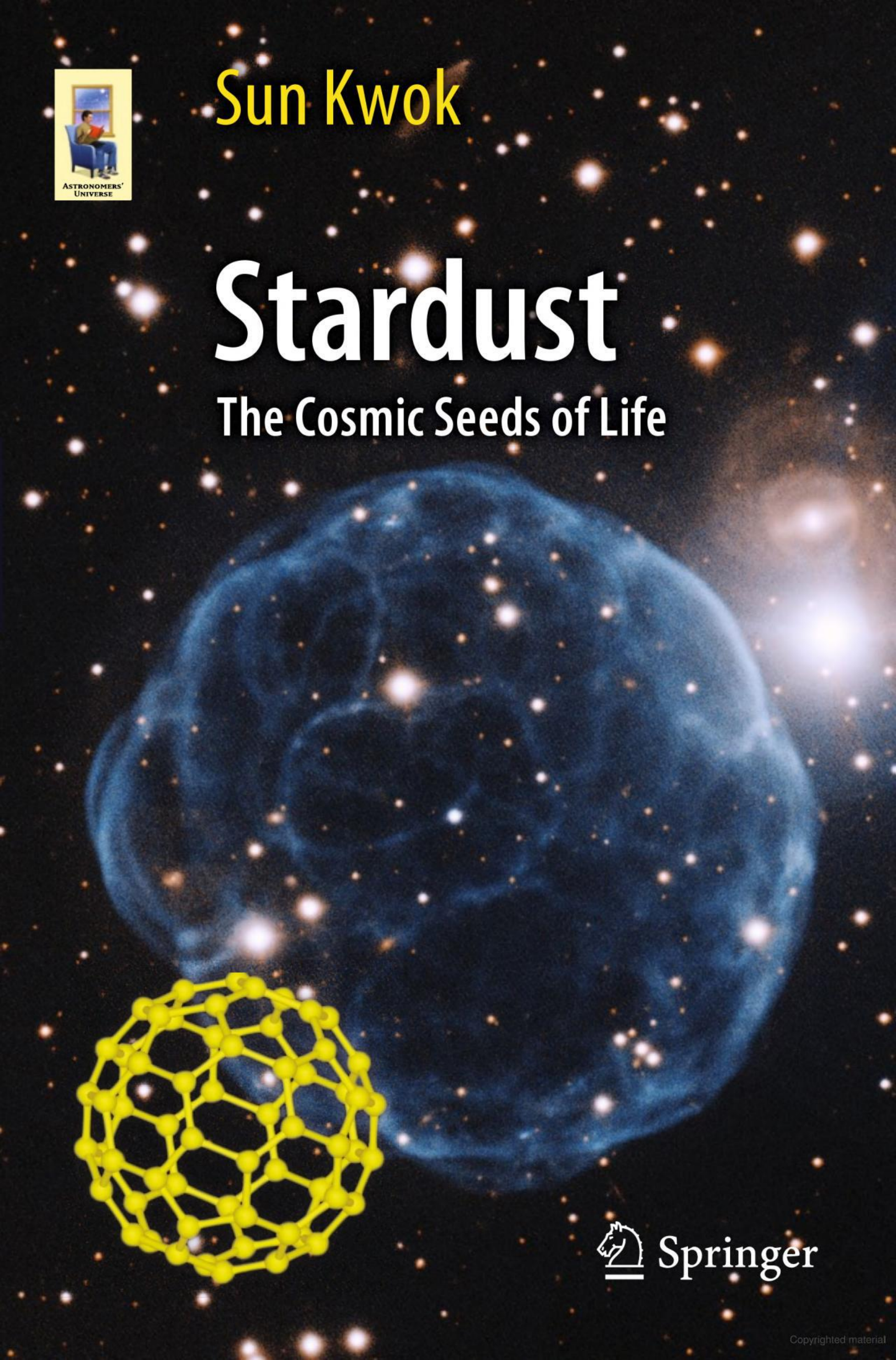
Sun Kwok

Stardust

The Cosmic Seeds of Life



Astronomers' Universe

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Contents

List of Figures

List of Tables

List of Boxes

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

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[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

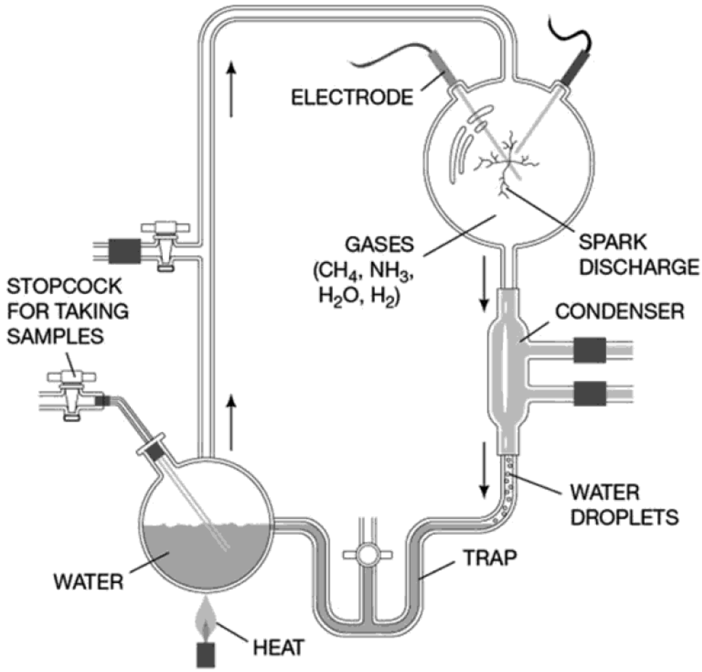

Fig. 1.1 The Miller–Urey experiment.
The experiment consists of a simple flask (*upper right*) containing a mixture of methane, ammonia, water and hydrogen. An electric spark is introduced. The chemical reaction products collected include amino acids and other complex organics, showing that biomolecules can be synthesized naturally under conditions of the early Earth

suggested that the atmosphere of the early Earth had a composition made up of water, ammonia, and methane but no oxygen. Miller wanted to test what kind of chemistry could be at work under conditions of the early Earth. Urey had thought that for interesting results to emerge, the experiment had to run a very long time. Everyone was surprised when Miller observed the presence of amino acids in the flask after only a few days. The experiment was reported in the journal *Science*. Legend has it that although Miller initially put Urey's name on the paper, Urey declined citing that "I already have a Nobel Prize" and left his student to take full credit for the discovery. The Miller–Urey experiment was described by Carl Sagan as "the single most significant step in convincing many scientists that life is likely to be abundant in the cosmos." For the second half of the twentieth century, the theory of life emerging spontaneously from simple molecules in a primordial soup in the young Earth became widely accepted by the scientific community.

Another theory of the origin of life considers the possibility that life is common everywhere in the Universe and is spread from place to place. The hypothesis of panspermia stipulates that life on Earth originated from outside and was delivered to Earth. More than 2,000 years ago, the Greek philosopher Anaxagoras (~500

BC–428 BC), who discovered the nature of eclipses, had already outlined the principle of panspermia. He considered that the seeds of life are already in the Universe, and they will take root whenever the conditions become favorable.

Back in 1871, the German physiologist Hermann von Helmholtz (1821–1894) wrote that "who could say whether the comets and meteors which swam everywhere through space, may not scatter germs wherever a new world has reached the stage in which it is a suitable place for organic beings." The Swedish chemist Svante Arrhenius (1859–1927) promoted in his book "*Worlds in the Making*" in 1904 (1 year after he won the Nobel Prize—the first Swede to receive the honor) the idea that simple life forms (e.g. bacteria) spread from star to star by long journeys through the interstellar medium. His idea was that small particles containing seeds of life could be propelled between planetary systems by radiation pressure, the force that light exerts on solid bodies. He believed that these spores frozen in the low temperature of interstellar space could be revived again once they reach favorable surroundings after journeys of thousands of years. However, there was no empirical evidence at the time for the mechanisms that he was considering and interest in panspermia died down in the 1920s.

While the external hypothesis does not solve the problem of the origin of life, but simply shifts the problem to somewhere else, it cannot be dismissed easily. It is quite possible that there are locations with more favorable conditions for the creation of life and we are the beneficiaries. The most widely promoted hypothesis of life arriving from space in recent times is in the works of Fred Hoyle (1915–2001) and Chandra Wickramsinghe. These authors argue that if life can develop from inorganic matter from Earth, life must have been common in millions of other solar systems as the Galaxy is old (~10 billion years). Living organisms from those systems could just as easily have been transported to our Solar System and seeded life on Earth. They also cited the fact that microorganisms can survive and indeed thrive under extreme conditions as evidence that bacteria can endure long interstellar journeys. The analogs of bacteria revived from bees embedded in amber for 25–40 million years and in 250 million year old salt crystals have also been cited as evidence of the viability of panspermia.

If the Oparin-Haldane hypothesis is correct that life on Earth originated from simple inorganic molecules, then similar processes could also be at work elsewhere. This possibility was raised in the book *Life in the Universe* by Oparin and Soviet astronomer V. Fesenkov in 1956. Technological advances, in particular in the form of the space program in the U.S. and in the Soviet Union, heightened the hope that extraterrestrial life could become a subject for experimental studies. Probes and landers to the Moon and Mars could search for signs of life. The first serious attempts to address this question were the two *Viking* spacecrafts which landed on the surface of Mars in July and September of 1976. The *Viking missions* were equipped with biological experiments to search for signs of metabolic activities as signs of life. While the experiments found that the surface of Mars was chemically active, there were no definite indications of biological activity. By the end of the mission, scientists came to the reluctant conclusion that extraterrestrial life has not been found on Mars.

As of 2012, there has been no empirical evidence for the existence of extraterrestrial life forms such as bacteria anywhere in the Solar System, or beyond. However, it has been known since the mid-nineteenth century that meteorites contain organic material. The Alais meteorite that fell in Alais, France, in 1806 and the Kaba meteorite that fell near Debrecen, Hungary, in April, 1857, were found to be rich in organics upon analysis. This was the first indication that complex organic materials may not be the sole domain of the Earth, and are actually present beyond the Earth, at least in the Solar System. In the nineteenth century, and as a matter of fact during most of the twentieth century, it was commonly believed that life on Earth was unique, and organic matter should only be found on Earth. The concept that organic matter resides in meteorites originating outside of the Earth did not take hold until the mid-twentieth century, although evidence for it had been around for over a century.

At the beginning of the twenty-first century, here is how we stand on the question of origin of life on Earth. On one side we have the chemical origin of life in the form of the Oparin-Haldane hypothesis and support from the Miller–Urey experiment. On the other side we have the biological delivery in the form of the theory of panspermia of Arrhenius and Hoyle and Wickramsinghe. Is there a middle ground? We now know that organic matter is not only present in the Solar System, but elsewhere in the Universe as well. In this book, we will tell the story of how we come to learn that organic matter is prevalent throughout the Universe. We now know that stars can make large quantities of organic compounds efficiently. These organics are contained in stardust, tiny specks of solids manufactured by stars. We have found that such stardust particles are made in the last one million years of a star's life, and they are spread throughout the Milky Way Galaxy. After a long journey through space, they became part of our early Solar System, and we now have direct evidence of their presence in our midst. We will describe how we learned about the existence of organic matter in the Universe, how we discovered that stars are capable of producing organics, and how these stellar materials might have had an effect on the origin of life on Earth.

A brief summary of this chapter
How we learned about organic matter in universe, about stars producing organics, how they might affect origin of life on Earth.

Key words and concepts in this chapter
- History of hypotheses on the origin of life
- Supernatural, extraterrestrial intervention, spontaneous creation
- Vital force as a component of organic matter
- Biological forms and functions can be explained by biochemistry
- Oparin-Haldane hypothesis for a chemical origin of life
- The Miller–Urey experiment as a simulation of chemical processes leading to life

- Panspermia
- Organic matter in the Universe

Questions to think about

1. Even as early as 4,000 years ago, ancient people already pondered about the question of the beginning of humans. Why do you think humans had the need and urge to seek an answer to this question?
2. What do you think of the concept of "vitality"? Is it reasonable to think that the living and the non-living are distinguished by something significant?
3. Energy is also an abstract entity that we cannot touch or feel. Is it more real than vitality?
4. What do you think of the field of biochemistry on philosophical grounds? Is it a reasonable assumption that biology can be reduced to chemistry?
5. Why is the Miller–Urey experiment significant? Why didn't people think of doing this before?
6. Do you think that life is unique? As of 2012, there is no evidence for the existence of extraterrestrial life. Do you think that there is life beyond the Earth?

Chapter 2
Rocks and Dust in the Planetary Neighborhood

The planet we live on, the Earth, is a chunk of rock partially covered with liquid water and overlaid with a thin blanket of gaseous atmosphere. Liquid oceans and polar ice caps cover three quarters of the Earth's surface. The continents, on which we walk and build our cities and villages, are made up of rocks. However, the rocky crust of the Earth is not limited to the continents, but extends to the ocean floors. These rocks are aggregates of minerals, which are solid-state compounds of common elements such as oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium. Three of our Solar System neighbors, Mercury, Venus, and Mars, have similar rocky surfaces and the four together are collectively known as the "terrestrial planets". The rocky nature of Mars is most vividly illustrated by the landscape images sent back by the Martian rovers *Spirit*, *Opportunity*, and *Curiosity*. In contrast, the other four planets in the outer Solar System—Jupiter, Saturn, Uranus, and Neptune —are gaseous in nature and do not possess a solid surface. The only anomaly is Pluto, the outermost member, which is believed to be made up of water ice and is no longer considered a planet.

Most planets have moons that revolve around them. Our own Moon, the only natural satellite of the Earth, is also rocky. When Galileo Galilei (1564–1642) observed the Moon with a telescope in 1610, he did not find a perfect, smooth celestial body, but instead an uneven and rough surface. The majority of the topographical features of the Moon turned out to be craters, or scars left over from external impact events. The rocky nature of the Moon is clearly illustrated by the Apollo astronauts who walked and drove vehicles on the surface of the Moon. Other planetary satellites, such as the Martian moons Phobos and Deimos, are also rocky. So are the moons of Jupiter such as Io, Europa, Ganymede, and Callisto. So is the largest moon of Saturn–Titan. Pictures brought back by the European Space Agency's *Huygens probe* showed the rocky nature of Titan's surface most clearly and dramatically (Fig. 2.1).

On a smaller scale, there are the asteroids. Asteroids are small, rocky objects that revolve around the Sun. The largest asteroid known, Ceres, has a size of 940 km and a mass 10,000th that of the Earth. Many asteroids are concentrated in the "asteroid belt" between the orbits of Mars and Jupiter. The number of asteroids known

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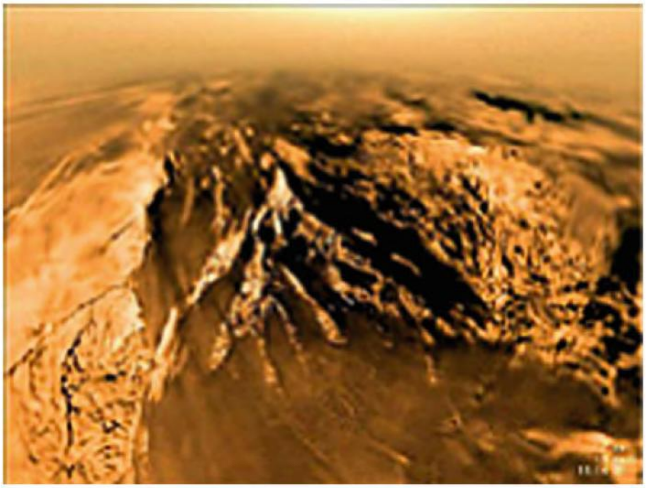

Fig. 2.1 A view of Titan's surface taken by the *Huygens probe*.
A view of the surface of Titan as taken by the *Huygens probe* during its fall through Titan's atmosphere after its release from the *Cassini* spacecraft on January 14, 2005. Photo credit: ESA

Fig. 2.2 Images of the asteroids Gaspra and Ida.
These images of Gaspra (*left*) and Ida (*right*) were taken by the *Galileo* spacecraft. Marks left by past impacts can clearly be seen on the surface. The longest dimension is about 20 km for Gaspra and 50 km for Ida. Photo credit: NASA/JPL

exceeds 100,000, a number likely to increase rapidly as larger telescopes are put into action for their search. Close-up photographs taken by spacecrafts have revealed that asteroids are irregular objects. When the *Galileo* spacecraft flew by the asteroid 951 Gaspra on October 29, 1991, the pictures of the asteroid showed that its surface is marred by deep scars created by a long history of impact events. The images of Gaspra and Ida (Fig. 2.2) and of Vesta (Fig. 2.3) definitely carry home the message that these heavenly bodies look very much like ordinary rocks.

If asteroids are rocky, then it would be possible to land on them. Indeed a Japanese space mission did exactly that. The *Hayabusa mission* was launched on May 9, 2003 and reached asteroid 25143 Itokawa in September 2005. It descended on the asteroid in November 2005 and collected samples from the surface of the

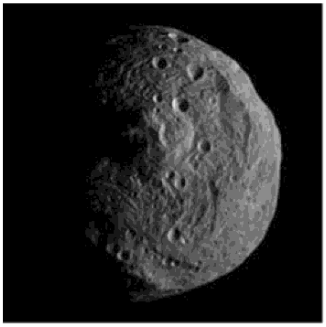

Fig. 2.3 Image of the asteroid Vesta.
This picture of Vesta was taken by the *Dawn* spacecraft. *Dawn* was launched in September 2007 and reached the asteroid in July 2011 after an almost 4 year journey across the Solar System. At a distance of 41,000 km, the surface of Vesta can be clearly seen to have a rocky appearance. The main difference between asteroids and the Earth and the Moon is that they are not necessarily spherical in shape. However, Vesta is nearly spherical with a diameter of about 500 km. Photo credit: NASA/JPL

asteroid before returning to Earth on June 13, 2010. A capsule containing the rock sample was released from the spacecraft and landed safely in Australia. Although the amount of asteroid materials contained in the return sample was small, it did allow scientists a direct look into the chemical composition of the asteroid and establish the asteroid origin of some of the meteorites collected on Earth.

How small can an asteroid be? There is no clear definition on the minimum size of an asteroid. We do know that solid debris of all sizes are present in the interplanetary space. The commonly used dividing line is a size of 100 m, although this is entirely arbitrary. Any object larger than 100 m is called an asteroid, smaller a “meteoroid”, which we define as small asteroids with orbits around the Sun that cross the Earth’s orbit. When a meteoroid enters the Earth’s atmosphere, the friction of its fall heats up the surrounding air, leading to a streak of light across the sky which we see as a meteor (commonly known as a “shooting star”). Although now we can predict the coming of meteor showers, we still cannot predict the exact occurrence of an individual meteor. Meteors are examples of the changeable nature of the heavens. Although the Sun, the Moon, the stars, and the planets all have regular, predictable movement patterns in the sky, the coming of meteors cannot be predicted. Such unpredictable events in the heavens have been used for astrological purposes. For example, the occurrence of a meteor was interpreted in China as a sign for the fall of a major figure, a court official, a commanding general.

On a typical clear moonless night, several meteors can be observed in an hour across the sky. These are called sporadic meteors as their appearance can be sudden and unpredictable, and they seem to appear in random directions in the sky. These are in contrast to shower meteors, which seem to originate from a fixed point in the sky and can be expected to occur at certain times of the year. For example, a meteor shower that occurs every August seems to radiate from the constellation of Perseus and is named the Perseid meteor shower. In 1833, a spectacular meteor shower was

Fig. 2.4 Engraving showing the 1833 Leonid meteor showers.
Meteor showers can be dramatic events as seen in this engraving showing the 1833 Leonid meteor showers

seen to come from the constellation of Leo (Fig. 2.4). It has been said that the great meteor shower of 1833 was responsible for the ignition of public interest in astronomical research in the USA. This meteor shower, named the Leonid meteor shower, had a repeat performance on 1866. In fact, the historical record shows that this same meteor shower has been observed as early as 899 AD. We now know that the periodic nature of meteor showers is related to earth-orbit crossing comets (Chap. 18).

As a meteoroid passes through the atmosphere it burns itself up due to atmospheric friction and gives off visible light in the process. It may also fragment into multiple pieces. Sometimes a meteoroid will be completely vaporized in its passage through the atmosphere. In fact, most meteoroids lose most of their mass. If a fraction of the meteoroid survives at all through the atmosphere, its remnant on the ground is called a meteorite.

Falls of meteorites have been recorded throughout history, dating back over 1,000 years. The oldest meteorite fall on record is the Nogata meteorite recovered in Japan on May 19, 861 A.D. The earliest European record was that of the Ensisheim meteorite in 1492. The meteorite that fell on June 16, 1794 was at a location near a major European city, Siena, Italy, and was witnessed by many people. In spite of the numerous reports of meteorite falls in Europe, they were not taken seriously. In China, Japan, and Korea, imperial and provincial records contained hundreds of reported cases of meteorite falls, but there was little interest in seeking out the origin of these events. In Europe, the more religious considered meteorites to be acts of the devil. Those who were brave or imaginative enough to suggest otherwise were condemned as heretics. There was a strong belief that the heavens are divine, holy, and unchanging. Since the time of Aristotle, the celestial sphere was seen to be separate and detached from the terrestrial earth, where hurricanes, floods, volcanos, earthquakes, and other unpredictable misfortunes happen. In religious circles, such calamities were commonly believed to be caused by sins of men. This is in stark contrast to the heavens which are peaceful and everlasting. There was a strong reluctance to associate temporal phenomena such as meteors with anything in the celestial sphere. Mud and rocks are supposed to be confined to the domains of the Earth, and could not have descended from the heavens.

Even in modern times, meteorites were thought to be created in the atmosphere by lightning, or by accretion of volcanic dust. One of the most famous quotes was that of Thomas Jefferson (1743–1826), who reacted to the reported 1807 fall of a meteorite in Connecticut with the comment “it is easier to believe that two Yankee professors would lie than that stones should fall from heaven”. In 1794, a German scientist, Ernst Friederick Chladni (1756–1827), suggested that meteorites are the result of fireballs, and meteorites do not originate from the clouds, but from outside of the Earth. His idea received no support from his contemporary scholars. In 1802, an English chemist, Edward Charles Howard (1774–1816), analyzed four meteorites and found their chemical composition to be similar but different from terrestrial rocks. It was the chemical analyses and microscopic examinations of meteorites that finally persuaded the scientific community of the extraterrestrial origin of meteorites and that did not happen until the early nineteenth century.

Before 1969, there were only 2100 known meteorites catalogued. The remarkable increase in the recovery of meteorites in recent years is due to the activities in Antarctica. Although meteorites fall randomly all over the world, the white, icy background of Antarctica makes it much easier to spot one. Also since the rocky surface of Antarctica is hidden below 3,000 m of ice, any piece of rock one sees on the surface is likely to be extraterrestrial in origin. A meteorite fallen on ice is also less likely to have been damaged and is better preserved through time. The first meteorite in Antarctica was found in 1912, but in 1969, the Japanese Antarctic Research Expedition found 9 meteorites near Yamato Mountains and realized that the movement of ice sheets can bring meteorites close together in concentrated groups. Since then there have been many search programs by different countries. For example, the American Antarctic Search for Meteorites (ANSMET) team has recovered over 20,000 meteorites. As of 2012, there are over 45,000 known meteorites. Other promising recovery sites are deserts, where the barren landscape also allows for easy identification. Successful recoveries have been made in deserts in Chile, Namibia, and Australia.

One good thing about meteorites is that we can pick them up and examine them. An initial impression of meteorites is that they resemble rocks. This in itself is significant, as meteorites are extraterrestrial objects; we have direct, first-hand experience that there are rocks in the sky. However, they are on average heavier than a rock of similar size on Earth.

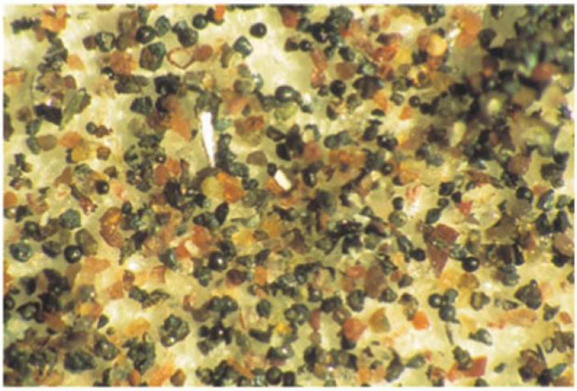

Fig. 2.5 Micrometeorites collected in Antarctica. This sample of micrometeorites was collected by a French–Italian expedition to Antarctica in 2003. Image credit: CNRS Photothèque, Michel Maurette

Although we generally associate meteoroids with macroscopic objects of meters or centimeters in size, the remnants of small meteoroids (those of golf balls or marbles sizes) may leave too small a remnant to be seen by the eye. A very small meteoroid (with sizes smaller than a millimeter) may even float through the atmosphere without burning. The remnants of these meteoroids are called micrometeorites (Fig. 2.5). Samples of these particles have been collected in Greenland and Antarctica where they are easier to spot on an ice/snow surface. From the collected samples, it is estimated every year 40,000 tons of micrometeorites land on the Earth.

Our current thinking of the origin of micrometeorites is that they are remnants of comets. Since micrometeorites come from space, they must be flying around in interplanetary space. As solid objects, the terrestrial planets, moons, and asteroids can reflect sunlight and can be seen as bright visual objects in the sky. Smaller solids like meteoroids can also be seen as meteors as they burn through the atmosphere.

Although meteorites can be found by just random searching of the ground, they are much easier to find if we know that one is falling. The fall of a large meteorite is often accompanied by bright fireballs and loud sonic booms. On average, two or three large fireballs are observed worldwide per night. In a way, a fireball is just a very bright meteor (Fig. 2.6). The International Astronomical Union defines a fireball as a meteor that is brighter than any of the planets. These falls often create quite an alarm among the populations that witnessed them. Nowadays, the sky is systematically watched for fireballs through the installation of a system of wide-angle cameras. By comparing the images of the fireballs in different cameras, the location of the fall can be identified, therefore increasing the chance of recovering the meteorite.

One of the earliest records of tracking the fall of a meteorite is the meteorite that landed near Orgueil in southern France on May 14, 1864. A brilliant fireball accompanied by loud explosions was seen and heard all over southern France shortly after 8 PM. Most of the stones fell near the village of Orgueil and over 20 pieces of black rock were immediately collected by local villagers. The largest

Fig. 2.6 Fireballs.
This picture of a fireball was taken on September 30, 2008 at the Black Mesa State Park in Oklahoma, USA by Howard Edin. This fireball meteor appeared about 2 AM and can be seen passing through the constellations of Taurus (*top*) and Orion. Photo credit: Howard Edin

Fig. 2.7 Carbonaceous chondrite meteorites. Carbonaceous chondrite meteorites such as the Allende shown in this picture are often black or dark gray in color, and are rich in carbon. These are the kinds of meteorites in which extraterrestrial organics are found. Photo credit: Toby Smith

piece is as large as a man's head, but typically the collected pieces are fist-sized objects. A total of 11.5 kg of the meteorite remnants were recovered, with the largest piece (9.3 kg) now residing in the Paris Museum. Between 1864 and 1894, 47 pieces of scholarly work were published on the meteorite.

As times moved on, scientists found that one of the distinguishing features of meteorites is their texture. Inside the meteorites are millimeter-size ellipsoidal structures called chondrules. The shapes and structures of the chondrules led us to believe that these chondrules were formed in a molten state. One special kind (about 4 % of all the meteorites that fall to the Earth) is called carbonaceous chondrites (Fig. 2.7). They are among the most primitive objects in the Solar System.

In 1834, a Swedish chemist, Jöns Jacob Berzelius (1779–1848), was the first to discover that meteorites contain organic materials. Berzelius was considered the

Fig. 2.8 Murchison meteorite.
The meteorite that fell near the town of Murchison, Australia, is one of the carbonaceous meteorites that are found to contain a large amount of organic material

father of Swedish chemistry and his proposed system of chemical notation using a combination of letters and numbers to signify elements and their proportions (e.g., H_2O) in a compound is still in use today. Confirmation of this discovery had to wait over a hundred years. In March, 1961, Bartholomew Nagy and Douglas Hennessy of Fordham University in New York, together with a petroleum chemist, Warren Meinschein, from the ESSO Research Corporation, reported in a meeting of the New York Academy of Sciences that they found hydrocarbons in the Orgueil meteorite that resemble products of life. Nagy and his team performed their analysis on a sample obtained from the Museum of Natural History in New York. They took incredible care to avoid the possibility of contamination. Using a mass spectrometer, they identified various hydrocarbons including paraffins similar to those found in animal products such as butter. From this study, Nagy concluded that these organic compounds are indications of biogenic activities beyond the Earth.

In a paper published 3 weeks after the New York meeting, John Desmond Bernal (1901–1971) of the University of London commented on Nagy's report and discussed the possible origin of the organics. If the hydrocarbons are the products of life, then they must have been inherited from a planetary body, from which the Orgueil meteorite originated. However, most bodies in the asteroid belt are believed to be too small and too dry to harbor life. He even speculated that the Orgueil meteorite could have been sent from the primitive Earth, and arrived back at the Earth after a journey lasting millions of years in interplanetary space. The possibility that the meteorite came from an Earth-like planet in another solar system was also mentioned. In any case, the presence of organics in meteorite is difficult to explain.

On September 28, 1969, half a ton of fragments of a meteorite fell near the town of Murchison in Victoria, Australia. Following a bright fireball and a loud boom, fragments of the fallen meteorite were found over an area larger than 13 square km. Individual pieces as large as 7 kg were recovered. A fragment of the Murchison meteorite is shown in Fig. 2.8. Analysis of the Murchison meteorite by John Cronin and Sandra Pizzarello of Arizona State University has shown they contain complex organic compounds with both aromatic (ring-like) and aliphatic (chain-like) structures. The term "aromatics" was first used in the mid-nineteenth century to refer to chemical substances with notable aromas, but now the term is used to refer to a class of molecules consisting of rings of six carbon atoms. The simplest example is benzene, which consists of six carbon atoms arranged in the form of a ring with six hydrogen atoms each attaching to one carbon atom. In contrast, aliphatic compounds consist of carbon atoms arranged in the form of a chain. Both aromatic and aliphatic compounds form the basis of molecules of life. Many common biochemical substances, including amino acids, fatty acids, purines, pyrimidines, and sugars are found in the Murchison meteorite.

One of the people who has contributed much to our modern understanding of organics in meteorites is Sandra Pizzarello. She was originally from Venice, Italy and already had four children before she moved to the U.S. with her husband. When her youngest child went to grade school, she decided to go back to university to study biochemistry. One of her teachers was a young professor named John Cronin. From that point on, Pizzarello and Cronin carried on decades of collaboration, discovering and analyzing organics in meteorites.

On the morning of January 18, 2000, a fireball appeared in the sky of the Yukon Territory of Canada, and the colorful event lasting over 10 min was witnessed by hundreds of observers. However, subsequent aerial flights were unable to find a crater or a site of impact of the meteorite. Fortunately, fragments were found within 1 week on the frozen surface of Tagish Lake. This is a big break for scientists as the frozen lake was perfect for keeping the meteorite in pristine condition.

I consider meteorites gifts from heaven, as they give us the direct and complete access to extraterrestrial material. We can examine meteorites by visual inspection, subject them to passive observations by instruments, as well as perform active manipulations by experiments. This is far superior to the limited ability of remote astronomical observations of celestial objects. We can measure and determine their physical and chemical properties, and derive the abundance of various chemical components as well as their isotopic ratios. Laboratory techniques that have been applied to meteorites include spectroscopy, nuclear magnetic resonance (NMR), X-ray absorption near-edge structure (XANES), and electron paramagnetic resonance (EPR).

If we go to the countryside away from the artificial light of the cities and step out about 1 h after sunset on a clear, moonless evening in the Spring, we can see a cone of diffuse light shaped like a pyramid spread out near the horizon with the brightest region near the point where the Sun has just set. This cone of light is called the zodiacal light (Fig. 2.9). The zodiacal light is best viewed from the tropics near the equator as it spreads out high in the sky. At high Northern or Southern latitudes, the zodiacal light lies closer to the horizon. At its best, the brightness of the zodiacal light can rival that of the Milky Way. However, the nature of the two is very different. Although it appears diffuse to the naked eye, the Milky Way is made up of light from billions of distant stars in our Galaxy (Fig. 2.10). The zodiacal light is much closer; it originates from the ecliptic, the plane in the Solar System where most of the orbits of the planets lie. If we observe the zodiacal light with a telescope, we will not be able to separate it into distinct stars. In fact, the zodiacal light originates from sunlight reflected by a large collection of tiny dust particles on the ecliptic plane. These particles are so small that we cannot see them with our eyes if we hold them in our hands. The particles that are responsible for the zodiacal light have sizes between a fraction of a micrometer (μm, or one thousandth of a millimeter) to several micrometers and they are called interplanetary dust particles.

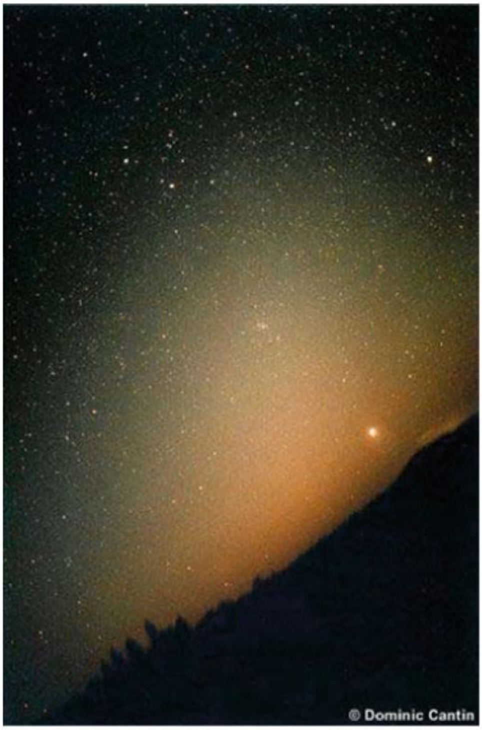

Fig. 2.9 Zodiacal light. This picture of the Zodiacal Light was photographed by Dominic Cantin near Quebec City, Canada. The bright spot near the horizon is the planet Venus. Photo credit: Dominic Cantin

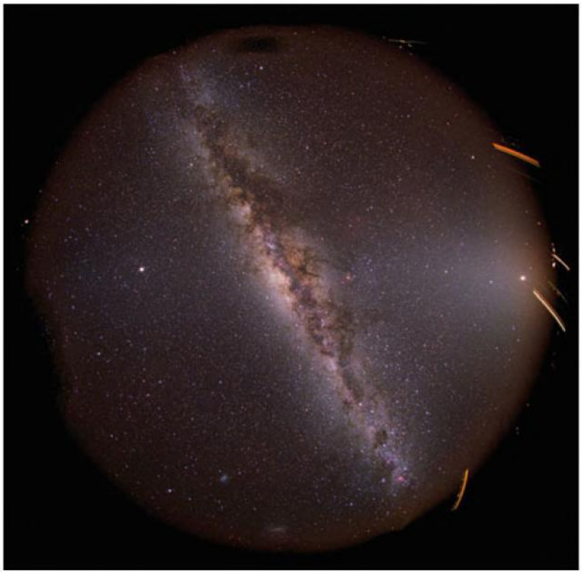

Fig. 2.10 The Milky Way. A panoramic view of the Milky Way. The dark patches in this picture are due to absorption by interstellar dust along the light of sight. The center of the Milky Way galaxy is located in the constellation Sagittarius, close to the border of Scorpius and Ophiuchus. Photo credit: Wei-Hao Wang

A brief summary of this chapter

Earth and surroundings have a lot of solid materials. Earth is not a closed environment.

Key words and concepts in this chapter

- Different forms of solids in the Solar System
- Planets and planetary satellites
- Asteroids
- Meteoroids, meteors, meteorites, and micrometeorites
- Extraterrestrial origin of meteorites
- Organics in the Orgueil and Murchison meteorites
- Zodiacal light and interplanetary dust particles
- Kuiper Belt objects
- Rain from heaven

Questions to think about

1. Is it surprising that there can be rocks that fall from the sky? Put yourself in the minds of people 200 years ago and discuss why it was so difficult for people to accept the extraterrestrial origin of meteorites.
2. Meteorites provide us a link to the extraterrestrial world. What are our other links? Can you compare the effectiveness of these links in learning about the extraterrestrial world?
3. At the meeting of the New York Academy of Sciences in 1961, Nagy, Meinshein and Hennessy were quoted to state that "biogenic processes occur and that living forms exist in regions of the universe beyond the earth" (Bernal, J.D. 1961, *Nature*, **190**, 129). Do you think it is possible?
4. Since the beginning of the twentieth century, astronomers have been studying galaxies as far as billions of light years away. The Kuiper Belt is in our Solar System and is relatively nearby, but they were not known until the late twentieth century. Why did astronomers pursue objects so distant and at the same time were so ignorant about objects in our own backyard?
5. The Earth is subjected to a constant rain of external fine dust particles at a rate of a hundred tons a day. What are the effects of this rain? Should we be concerned about it?

Chapter 3
Impacts from Beyond

Geologists have long been familiar with volcanic eruptions and it is known that the eruption openings of volcanoes form circular depressions which are called craters. A large fallen meteoroid, say, one weighing a ton and over a meter in size, hitting the surface of the Earth can leave a large mark on Earth. Suspecting that there were major meteoroid[1] impacts in the past, planetary scientists speculated that there could be remnant marks of these impacts today. However, it was not known what shape or form these marks would have. As it turned out, the terrestrial marks left by impacts look quite similar to volcanic craters, leading to a long delay in the identification of impact craters on Earth.

One of the best known terrestrial impact craters is the crater in Arizona (Fig. 3.1). It was discovered in the late 1870s by cattlemen driving herds across the land. Its shape looked like an extinct volcano and that was what it was thought to be. The only strange thing was that this crater was ringed with pure iron. Suspecting that this may be related to a meteoroid impact, a prominent geologist, Grove K. Gilbert (1843–1918) of the US Geological Survey, visited the crater in 1892 and concluded that it was the result of a volcanic steam explosion. Gilbert built his reputation through his exploration of the American West, having traveled by foot and on mule in Utah, Arizona, and New Mexico. His studies of the geological formations of the West made him the most respected American geologist at the time, having been elected twice (1892 and 1909) as president of the Geological Society of America. Don Wilhelms, in his book "*To a Rocky Moon*", called Gilbert "one of the greatest geologists who ever lived". There are craters on the Moon and Mars named after him.

Given Gilbert's stature, his ruling on the origin of the crater was not questioned. A lone amateur, Daniel M. Barringer (1860–1929), who was a mining engineer but not a geologist, challenged this common belief and performed extensive drilling in search for an iron mass as evidence for impact. Believing that the impact must have left a large meteorite and therefore an enormous mass of iron beneath the crater, he obtained mining rights for the land in and around the crater in an attempt to mine the

[1] A meteoroid is a small asteroid, see definition in Chap. 2.

S. Kwok, *Stardust*, Astronomers' Universe, DOI 10.1007/978-3-642-32802-2_3,

Fig. 3.1 The Barringer Crater.
The Canyon Diablo Crater, also known as the Barringer Crater, in Arizona has a diameter of 1 km and a depth of 170 m. It was created by a meteoroid impact about 50,000 years ago. Although originally believed to be a volcano, it was identified by Daniel Barringer as an impact crater. Photo credit: David Roddy and the U.S. Geological Survey

iron. Between 1903 and 1909, he drilled 28 holes to the depth of 250 m. By 1923, he has spent $600,000 of his fortune on this venture. By the time of his death in 1929, no iron mass was found. He was eventually vindicated when it was realized that the incoming meteoroid must have been completely vaporized upon impact and the crater is now named in his honor. The idea that craters are created by impact from extraterrestrial objects was not widely accepted in the geological community until the 1960s.

Since that time, over 100 impact craters larger than 100 m resulting from extraterrestrial impacts have been identified on Earth. The energy release in such impacts can rival that of a nuclear bomb. Although the bulk of the remnant of the object is melted or vaporized, fragments of it could survive and be found in the vicinity of the crater.

When we look at the Moon with a small telescope, we can see that the surface of the Moon is filled with craters. With the beginning of lunar missions in the 1960s, high quality images of the Moon obtained by lunar orbiting satellites have given us detailed morphologies and size measurements of the craters (Fig. 3.2). Why does the Moon look so different from the Earth, and where do these craters come from? For a long time scientists believed that craters on the Moon were volcanic in origin. As late as the mid-twentieth century, it was still a very popular belief in the Soviet Union that the lunar craters were created by volcanic eruptions. The first suggestion that the lunar craters are due to external impacts was made by Grove Gilbert. In October 1891, Gilbert observed the Moon for 18 nights using a 67-cm refracting telescope of the Naval Observatory in Washington.[2] He found that the largest lunar craters have sizes much larger than any crater on Earth. Lunar craters also come in many different sizes whereas volcanic craters on Earth have a definite size. This led him to suggest that the lunar craters are of impact origins. He also suggested that the

[2] The Naval Observatory is where the official residence of the Vice President is located.

Index

S. Kwok, *Stardust*, Astronomers' Universe, DOI 10.1007/978-3-642-32802-2,