ANDREW M. SHAW

ASTROCHEMISTRY

THE PHYSICAL CHEMISTRY OF THE UNIVERSE

SECOND 2 EDITION

with website

WILEY

Astrochemistry

Dedicated to My Family

Astrochemistry

The Physical Chemistry of the Universe

SECOND EDITION

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WILEY

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Preface to the First Edition

Astrochemistry draws its inspiration, language, fascination, beauty, elegance, and confusion from many different disciplines: starting with astronomy, passing through physical chemistry, and ending with the new ideas of astrobiology. It is this breadth of fascination that I have attempted to capture in *Astrochemistry: From Astronomy to Astrobiology*. Choosing such a broad subject comes with the serious problem of how to limit the discussion of the details to allow an appreciation of the whole. I could have written an entire book on molecular astrophysics, looking at what molecules are doing in the various environments of space. I could have looked simply at the wonders of planetary chemistry, concentrating on the solar system or even just one planet such as Jupiter. Why does it have a giant red spot? Instead, I have chosen to apply a more general boundary condition for the book taking in all of the subjects but focused on the theme of 'The Origin of Life'.

Astrochemistry starts with the origins of the Universe and the theory of the Big Bang, resulting in the formation of hydrogen, helium, and a little lithium. Gravity pulls the matter together to form stars, galaxies, and clusters of galaxies, all of which give off light in some form. The light tells the molecular story with information on the formation and evolution of stars and the role of atoms. At times these interesting subjects are buried in the disciplines of astronomy and astrophysics and I have tried to bring the pieces of the story together, concentrating on astrochemistry. The cycle of star formation ends with a supernova blowing huge quantities of material into the interstellar medium, now laden with all of the elements of the Periodic Table. Chemistry in the interstellar medium, with rather cold and tenuous conditions, is now possible and this controls the starting molecular inventory. To understand this fully, the subjects of quantum mechanics and kinetics need to be applied, through spectroscopy and chemical reaction networks, to the giant molecular clouds of the interstellar medium – the birthplace of stars and life?

Giant molecular clouds collapse to form stars and solar systems, with planets and debris left over such as comets and meteorites. Are comets and meteorites the delivery vehicles that enable life to start on many planets and move between the planets as the solar system forms, providing water and molecules to seed life? The planets have to be hospitable, however, and that seems to mean wet and warm. Carbon-based life forms and liquid water seem to be the successful life-experiment on Earth from which we can draw some more general conclusions about the requirements for life in a view towards astrobiology. A look at prebiotic chemistry and primitive life forms on Earth poses interesting questions such as what is a cell and how big does it have to be? The guiding principles for prebiotic chemistry are the laws of thermodynamics that keep the origins of life and its understanding on the straight and narrow.

Finally, and tantalizingly for this book and astrochemistry, there is Titan. The Cassini–Huygens mission is now in orbit in the Saturnian system as the book is published. The Huygens probe has already made the descent to the surface of Titan and the data have been transmitted back successfully. Scientists, astronomers, astrochemists, and astrobiologists are trying to understand it. I have taken a brief look at Titan as a case study to apply all that has been learnt and to review the possibilities for astrochemistry in what is surely to be a very exciting revelation of the structure and chemistry of Titan.

Throughout the book I have tried to constrain the wonders of imagination inspired by the subject by using simple calculations. Can all of the water on the Earth have been delivered by comets: if so, how many comets? How do I use molecular spectroscopy to work out what is happening in a giant molecular cloud? Calculations form part of the big hard-sell for astrochemistry and they provide a powerful control against myth. I have aimed the book at second-year undergraduates who have had some exposure to quantum mechanics, kinetics, thermodynamics, and mathematics but the book could easily be adapted as an introduction to all of these areas for a minor course in chemistry to stand alone.

Units and Conventions

Astronomy is probably the oldest of the subjects that influence astrochemistry and contains many ancient classifications and unit systems that have been preserved in the scientific research of today. Distances are measured in light-years or parsecs, neither of which are the standard SI unit of length: the metre. This is not surprising when a light-year is 9.5×10^{15} m and is a relatively small astronomical unit of length! The correct SI convention for a light-year would be 9.5 petametres, written as 9.5 Pm. This is formally correct but would not help you in a conversation with anybody, as most scientists cannot remember the SI prefixes above 10^{12}. I have listed the SI prefixes in Appendix A and we shall use them where appropriate. However, I will use two units of length chosen from astronomy, namely the light-year and the astronomical unit. The light-year is the distance travelled by light in 1 year or 86 400 s and 1 ly is 9.5 Pm or 9.5×10^{15} m. Usefully, the distance to the nearest star is some 4 ly. The other length unit is the astronomical unit (AU), which is the average distance from the Earth to the Sun and is 1.49×10^{11} m, with the entire solar system being approximately 150 000 AU and the distance to the nearest star some 300 000 AU.

The unit of time is the second in the fundamental list of constants but it is convenient to use years when referring to the age of the Universe, Solar System or the Earth. I have chosen to use the SI prefixes in front of the symbol yr so that 10^9 years is 1 Gyr; the age of the Universe is 15 billion years or 15 Gyr, etc., and whenever this refers to a period of time in the past then 4.5 Gyr ago will be used explicitly.

The conventions of chemistry, particularly physical chemistry, are standard and appear in all physical chemistry textbooks and will be used here. The same courtesy has been extended to organic and inorganic chemistry and biology, so that the ideas of these subjects can be linked into the common theme.

Course Material

I have put together a website for the book (www.wiley.co.uk/shawastrochemistry) where I have included the figures from the book to be downloaded into lectures. I have also included some links that I have found useful, corrections when required even some possible examination questions. I hope an adventurous professor will find these useful.

Acknowledgements

The book started as a survey of the literature to identify a research project, which in part it did, but during the work I discovered how interesting the subject can be and decided that it would make a good lecture course. The long-suffering students at the Department of Chemistry at Exeter University have enjoyed the course on two separate occasions and in two incarnations, most latterly as CHE2057 in 2005. The students saw the book at first draft and have contributed to removing the mistakes and suggested additions, pointing out where I said too much or too little. The refinements have helped and improved the text immeasurably. I have doubtlessly introduced more mistakes and for this I must take the full credit. The integrity of the book has been improved greatly by two very conscientious

reviewers, to whom I owe a debt of gratitude. I must extend thanks to all scientists around the world who helped to put together the figures for the book. Busy people spent valuable time collecting the images that have added to the wonder of the subject. The reward for writing the book will be the spark of curiosity that may flicker in the mind of the reader.

Andrew M. Shaw

Preface to the Second Edition

There are many reasons to update a textbook, the most important of which is that it gets out of date – at its core, it should be research-led. Astrochemistry and astrobiology have advanced significantly as fields driven by some truly remarkable planetary exploration science and astronomy. The Cassini-Huygens mission to the Saturnian moon Titan, hinted at in the first edition, sent back data to Earth with such extraordinary detail that I could not resist including an extended review of this hydrocarbon world. Similarly, the Mars rovers have now explored 31.81 miles on the Martian surface (Spirit 4.80 miles, and Opportunity 27.04 miles) at a sedate 12 miles per hour, digging up some interesting finds and consequences. We have also flown by Pluto for the first time, with the closest approach on 14 July 2015, changing Pluto from a 4-pixel world seen through the Hubble Space Telescope to a mysterious non-planet. Visits to asteroids, revisiting Mercury, discovering the Higgs boson, landing on a comet, the increased energy of the Large Hadron Collider, dark matter, Martian meteorites – this massively impressive list is a tribute to human endeavour and raw curiosity. It's important to track down these stories, and I have now referenced them throughout the book (not exhaustively, of course).

The principles of physical chemistry are universal, however, and their application to these new challenges is compelling – as was the change in the book's subtitle, *The Physical Chemistry of the Universe*. The application of physical chemistry to a diverse selection of research fields, seemingly unlinked at first, shows how a quantitative, mechanistic, deterministic approach to a problem is the best way to understand what is happening. In Chapter 5, I have developed the idea of deterministic models for interstellar medium chemistry that can be applied rigorously to atmospheres, interfaces, and surface and systems biology. This mechanistic approach is central to my research group, my spin-out companies, and the philosophy of the book. Inevitably, it involves some mathematics and coding in a high-level language such as Mathematica, WolframAlpha, or Matlab.

But physical chemistry is not a spectator sport, and the mathematics, calculations, and models must be tested using high-quality data, which involves hard mathematics. But surely mathematics is a ‘done deal’ given all of the powerful mathematics packages available? This may sound heretical, but algebra, integration, and differentiation can all be performed analytically using the computer packages; and the new, evolving physical chemistry skill is knowing how to set up a model and then how to test it – the implementation is almost a given. Knowledge itself is being computed, and there are now knowledge engines such as WolframAlpha that provide great power. Not only can it check the mathematics, but it can also answer questions and solve problems. I have incorporated references to WolframAlpha throughout the book, sometimes as interesting bits of information, other times as access to primary sources of data such as the NIST Atomic Spectra Database.

In addition to the book in paper form (which still provides a visceral human reading experience), the book is also available as an eBook, making the WolframAlpha links directly accessible. Completing the knowledge engine approach to the second edition is a set of CDF files on the website, supporting each of the chapters. These examples allow the reader to interact with the equations, change parameters, and derive information from the models. Similar interfaces are available in many complex modelling programmes and let the reader explore the model without the mathematical burden.

As you read the book and explore physical chemistry, consider the hypothesis that chemistry is fundamentally the interactions of energy and shape. *Shape* includes all the ideas of quantum mechanics: special allowed shapes and transitions, but also the idea that time is a shape the space-time dimension of special relativity (specifically, *ict*). Add energy to evolving shape, and there is a reasonable hypothesis for all of chemistry: extensions to astrochemistry and astrobiology are exciting examples.

The format of the book has changed: it is now larger and in full colour. Twenty problems are included at the end of each chapter, with some detailed solutions to give the reader the chance to exercise their mathematics (which becomes rusty very quickly if not used). I have added new sections on thermodynamics using meteor entry and included enzyme kinetics in the prebiotic lifeforms.

Acknowledgements

Thank you to all those students who have taken the course with me and provided feedback; the Norman Lockyer observatory, for making astronomy real; Dr Peter Reader, for some CDF files;

Wiley, for commissioning the second edition; and, critically, all of the people who bought the first edition. Countless texts and papers have influenced my thoughts; to those authors, my apologies if you have not been referenced fully.

Andrew M. Shaw
Winter, 2020

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/shaw2e

The website includes:

- PPTs of all the figures
- A selection CDFs relevant to each Chapter
- Chapter 3 - Video clip of the Pillars of Creation in 3D: https://www.ras.org.uk/news-and-press/2623-the-pillars-of-creation-in-3d

Scan this QR code to visit the companion website.

1

The Molecular Universe

Chemistry without numbers is poetry: astrochemistry without numbers is myth. A molecule placed around a star, in a nebula, lost in the interstellar medium, on a planet or within a cell has the potential for very complex and beautiful chemistry but unless we can understand the local conditions and how the molecule interacts with them, we have no idea what chemistry is really happening. To understand astrochemistry we need to understand the physical conditions that occur within the many diverse molecular environments. The exploration of the molecular universe will take us on a long journey through the wonders of astronomy to the new ideas of astrobiology but as we look out of the window, the physical chemistry of the Universe will continually challenge us and cause us to question everything.

The origins of life provide the motivation and excuse to investigate astrochemistry in its broadest sense, looking at molecules and their local complex chemistry using all of the tools of physical chemistry to constrain the imagination of the astrobiologist in the field and to force a re-think of the rules of biology that are prejudiced by the experience of life on Earth. The complexity of the problem places demands on the theories of science, stretching the understanding of kinetics and thermodynamics into areas where large non-ideal systems are hard to understand, although curiously, modelling the complex chemistry of a giant molecular cloud is not dissimilar to the models of biochemistry within a cell. The size of the chemical problem quickly grows, so that the chemistry of 120 molecules in a giant molecular cloud must be compared with the 4500 reactions thought to be required to make a cell work. The real understanding of the molecular mechanism only comes from a model of the network of coupled chemical equations forming a complex system: something as comparatively simple as a candle flame can contain 350 equations.

Astrochemistry: The Physical Chemistry of the Universe, Second Edition. Andrew M. Shaw.

Companion website: www.wiley.com/go/shaw2e

Our mission is to explore the molecular universe to develop an understanding of all the local molecular environments, constrain possible chemical reactions using the concepts of physical chemistry, and understand the potential for life on other worlds.

1.1 The Standard Model – Big Bang Theory

About 13.772 ± 0.059 billion years ago [1, 2] the Universe and time itself began in a Big Bang [3]. This is an impressively accurate number with a quantified error, music to the ears of a quantitative scientist such as a physical chemist. We shall see at various points how this number has become so accurate thanks to, amongst others, observations of the cosmic microwave background by the NASA Wilkinson Microwave Anisotropy Probe (WMAP) (http://map.gsfc.nasa.gov).

Observations of the night sky show that stars and galaxies are moving away from us, telling us that the Universe is expanding: extrapolating backwards in time leads to a point of common beginning, a singularity in space-time known as the Big Bang. A simple theory containing six parameters fits all of the current cosmological data [4]: the age of the universe, the density of atoms, the density of matter, the amplitude of the initial fluctuations, the scale dependence of this amplitude, and the epoch of first star formation. Along each line of sight observed by the WMAP satellite there is the history of the universe (Figure 1.1), from the period of uncertainty, the Planck epoch, through a massive inflation 180-*e* fold (*e* being the base of natural logarithms) during which very high-energy photons collided with one another, cooling at each collision until what is left is the cosmic microwave background (see Section 2.2). This afterglow is a snapshot of what was left after the first 375 000 years.

Temperature is critical to the phases of evolution and subsequent cooling of the Universe, producing a number of critical times, detailed in Table 1.1. They are all predictions of the Big Bang Theory or the Standard Model of Cosmic Evolution [3].

Einstein's theory of relativity allows for the interconversion of energy and matter through the famously simple equation $E = mc^2$. Thus, collisions between high-energy photons in the primordial fireball created particle–antiparticle pairs such as protons and antiprotons. After some 180 s and at a temperature of 10^9 K atomic nuclei such as hydrogen, deuterium, helium and some lithium were formed. The first three minutes of all time were chemically the dullest with no atoms or molecules. For a further 10^6 s the light atoms continue to be formed, marking a period where matter is created by *Big Bang nucleosynthesis*.

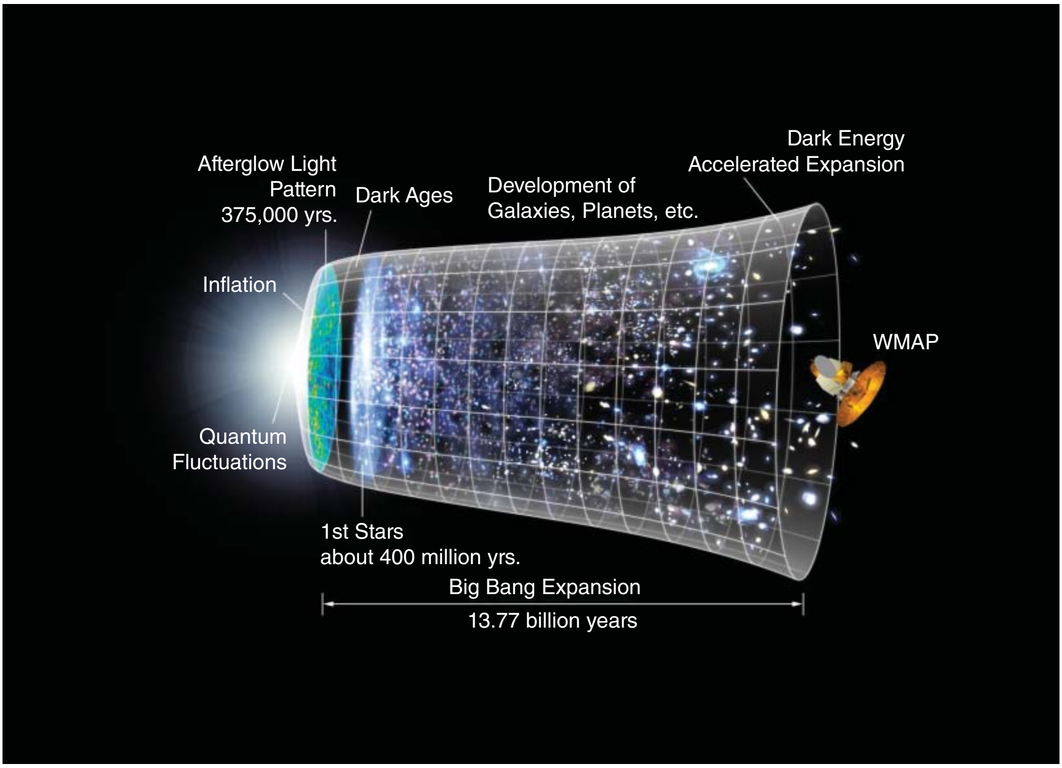

Figure 1.1 The cosmic timeline as it is observed today by the Wilkinson Microwave Anisotropy Probe (WMAP), which is studying the cosmic microwave background. The inflation cone shows what is happening/happened along one line of sight: they are obviously in all possible 4π-solid angle directions.

Table 1.1 The history of the Universe according to the Standard Model

Time since $t = 0$	Temperature	Comments
10^{-43} s	10^{32} K	Gravity is now distinct from the three other forces: strong, weak nuclear and electromagnetic.
10^{-35} s	10^{27} K	Inflation of the Universe – the strong force separates.
10^{-12} s	10^{15} K	Weak and electromagnetic forces separate. Neutrons and protons are formed by photon-photon collisions.
10^{-2} s	10^{11} K	Electrons and positrons are formed through collisions of photons.
1 s	10^{10} K	The Universe becomes transparent to neutrinos.
180 s	10^{9} K	Nucleosynthesis: hydrogen, deuterium, helium and some lithium.
$3–7 \times 10^{5}$ s	3000 K	Light element atoms form, and the Universe is now transparent to radiation: cosmic background is emitted.
10^{9} yr	20 K	Galaxies form.
Present	2.726 K	Stars and galaxies.

Source: Based on Ratra and Vogeley [3].

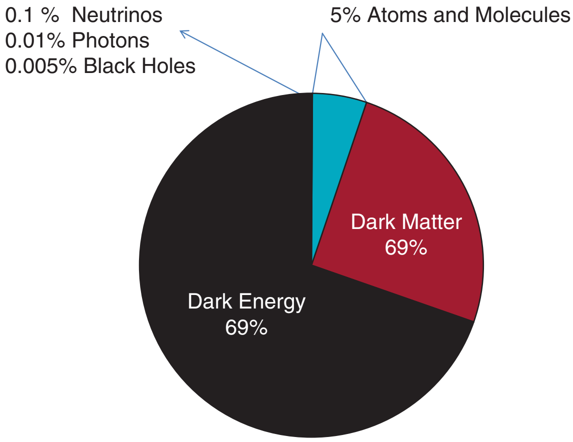

Figure 1.2 The proportions of each component of the Universe. Exact proportions are changing as the theories evolve, but astrochemistry comprises at most 5% of the universal problem. Source: Adapted from David N. Spergel [4].

There are a number of astronomical pieces of evidence for the Big Bang Theory as we shall see, including the recent observation of the cosmic microwave background radiation but it is far from a complete theory [1, 3, 5]. However, predictions of the theory may be tested. One such prediction is the relative abundance by mass of He, which must be at least 25% of the total mass. Helium is also made in stars and must contribute to the He density of the Universe and in all observations to date the observed abundance is greater than 25%. There are problems associated with matter. Why is the Universe made from matter instead of antimatter? When was this decision made to stabilise matter from high-energy photons and particle–antiparticle pairs. Further, calculations of gravitational attractions of galaxies suggest the presence of large amounts of matter that cannot be seen, so-called dark matter. What is dark matter? The current assessments of the relative portions of these rare cosmological substances is shown in Figure 1.2, although they are only the current estimates based on theories and rather fewer observations [4]. Astrochemistry makes up at most 5% of the problem.

The majority of the atomic Universe is made from hydrogen and helium produced during the Big Bang, although some He has been made subsequently. The relative cosmic abundance of some of the elements relevant to the formation of life is given in Table 1.2, with all elements heavier than H, He and Li made as a result of fusion processes within stars, as we shall see later. The cosmic abundance is assumed to be the same as the composition of the Sun.

Table 1.2 Relative cosmic abundance of the elements

Element	Relative abundance	Element	Relative abundance
H	1	S	1.6×10^{-5}
He	0.085	P	3.2×10^{-7}
Li	1.5×10^{-9}	Mg	3.5×10^{-5}
C	3.7×10^{-3}	Na	1.7×10^{-6}
N	1.2×10^{-3}	K	1.1×10^{-7}
O	6.7×10^{-3}	Si	3.6×10^{-6}

1.2 Galaxies, Stars, and Planets

After the initial photon collisions and formation of matter, all matter formed in the Big Bang is attracted to itself by the force of gravity, which finally results in the formation of the first proto-stars before there is any starlight. This period is called the *epoch of first star formation* or the *dark ages*. Within 1 billion years, the first massive proto-galaxies form. Gravitational contraction continues in more and more localised regions to form the galaxies we know today, including our galaxy, the Milky Way. The Milky Way, shown in Chapter 2, Figure 2.15, is in a cluster of galaxies called the *local group* (Figure 2.19), which includes the Large Magellanic Cloud, the Small Magellanic Cloud, and the Andromeda Galaxy (M31; Figure 2.15). Two of these, the Milky Way and the Andromeda Galaxy, are very luminous spiral galaxies.

Large Magellanic Cloud
Small Magellanic Cloud
Andromeda Galaxy (M31)
Milky Way

The Milky Way was formed within 1 billion years of the Big Bang and has a mass of 10^9 solar masses. It formed from a large cloud of hydrogen and helium that was slowly rotating. As the cloud collapsed, conservation of angular momentum required matter near the axis to rotate very fast. As a result, it spreads away from the axis and forms a flat spiralled disc some 120 000 ly in diameter and about 3300 ly thick. The Sun is approximately 30 000 ly from the centre. The nuclear bulge at the core of the galaxy contains old stars, and observations suggest that it must be hugely massive. Rapid rotation around the axis of the disc requires gravity and angular momentum, hence mass, to hold it together and this produced speculation about the existence of a black hole at the centre of the Milky Way.

The Sun formed some 4.5 Gyr ago (Gyr is a gigayear or 10^9 years) from its own gas cloud called the solar nebula, which consisted of mainly hydrogen but also all of the heavier elements that are observed in the spectrum of the Sun. Similarly, the elemental abundance on the Earth and all of the planets was defined by the composition of the solar nebula and so was ultimately responsible for the molecular inventory necessary for life. The solar system formed from a slowly rotating nebula that contracted around the proto-sun, forming the system of planets called the solar system. Astronomers have recently discovered solar systems around other stars, and in only the briefest of looks, this has revealed a large proportion of similar planetary systems: the formation of planets around stars is a common process. The distribution of mass in the solar system is primarily within the Sun but distributed rather differently among the planets. The inner planets, the so-called terrestrial planets of Mercury, Earth, Venus, and Mars, are essentially rocky; but Jupiter, Saturn, Uranus, and Neptune are huge gas giants. This needs to be explained by the formation process. Most important, however, is the formation of a planet in a habitable zone, where liquid water can exist and have the potential for life – at least if you follow the terrestrial model.

1.3 Origins of Life

The age of the Earth is established by radioisotope dating at 4.55 Gyr. For most of the first billion years it suffered major impact events capable of completely sterilising the Earth, removing any life forms – mass-extinction events. The geological fossil records reveal, however, that life existed some 3.5 Gyr ago and perhaps as early as 3.9 Gyr ago. The oldest known life forms were very simple by modern standards but already had hugely complicated structures involving membranes and genetic information. The rather surprising conclusion is that life may have developed in as little as 100 million years and at most 0.5 billion years, to evolve from the primordial soup to a viable living organism that had adapted to its local environment.

1.3.1 Definitions of Life

There are many problems with the definitions of life [6], although determining what is alive and what is not is intuitively easy. At the extremes of collections of matter are human beings and atoms, with all of the possibilities in between and beyond. Classical definitions of life taken from biology, such as ingesting nutrients, excreting by-products, growth, and reproduction, all serve as good markers of life, although they are almost certainly prejudiced by life on Earth. What about fire? A candle flame (Figure 1.3) clearly ingests nutrients from the air in the form of oxygen and fuel from the wax. It produces waste products; it can also grow to cover large areas and certainly looks as if it might reproduce itself by creating new fires through sparks. It is localised by both a temperature and a concentration gradient and might indeed be alive. However, one flame does become a copy of itself in that it will burn whatever fuel and oxidant

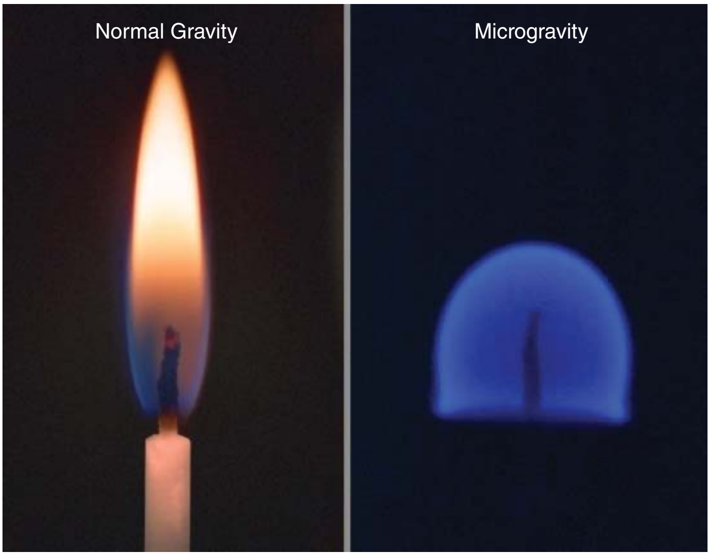

Figure 1.3 Two species of candle flame – dead or alive? The flame on the left is on Earth, and the flame on the right is burning under zero gravity. Source: Photos by courtesy of NASA.

combination available to it. In a sense, it evolves and lives for as long as it can adapt to its environment. The adaptation to the environment is seen on the right-hand side of Figure 1.3, where a candle flame is burning under conditions of zero gravity in the space shuttle. The shape of the flame in air is controlled by buoyancy: the hot air inside the candle flame air is less dense than the air around it, and it rises. In zero gravity the hot air does not rise, because its weight is zero, and so the random thermal motion results in diffusion of oxygen into the flame and combustions products away from the flame; hence the flame is now spherical. Even a complex set of chemical reactions, recognisable as a flame, has adapted to the environment. There is a consistent chemistry set within the 350 equations required to get the flame ‘metabolism’ chemistry to burn properly and, as such, it contains a recipe or DNA. Other more impressively vague twilight life forms must include virus particles.

Viruses have no real metabolism and appear to exist in a dormant state until they find a suitable host. Then they hijack the metabolism and DNA replication apparatus of the host cell, switching the host into the production of huge numbers of copied virus particles, including some mutations for good measure. Finally, the cell bursts and the virus particles are released to infect a new host. The propagation of genetic information is important, as is the need for some form of randomisation process in the form of mutations, but it is not clear that there can be one definition for life itself. NASA has chosen the following definition:

> *Life is a self-sustained chemical system capable of undergoing Darwinian evolution.*

Alternatively, my definition in the first edition was:

> *A system that is capable of metabolism and propagation of information.*

And this remains reasonable. Others are equally struck by the concept of information propagation [6].

1.3.2 Specialisation and Adaptation

Cellular life may have arisen spontaneously, capturing whatever prebiotic debris that was present in the primordial soup. The encapsulation process provided the first specialisation within the environment, leading to compartmentalisation firstly from the external environment and then within the cell to provide areas of the protocell with dedicated adapted function. The external barrier in biology is provided by a cell membrane constructed from a bilayer of phospholipids with added sugars to make it rigid. The phospholipid molecules are amphiphilic, containing a long fatty acid chain of 10–20 carbon atoms at one end that are hydrophobic and a phosphate head group at the other end that is hydrophilic. It is the hydrophobic–hydrophilic characteristic at different ends of the molecule that make it amphiphilic. These molecules spontaneously form vesicles and membranes called liposomes in water when the concentration is above the critical micelle concentration. The network of chemical reactions trapped within a liposome could easily form a proto-metabolism but there is still the need for an information-bearing polymer.

Looking again at biology, genetic information is stored in all organisms as either DNA or RNA. These huge polymeric molecules contain the information for the replication of the building blocks of all organisms, the proteins. The four bases, G, A, T, and C, pair together as A–T and G–C, the so-called *Watson–Crick base pairs*, which together with the deoxyribose sugar and phosphate backbone form the α-helix of the DNA molecule as shown in Figure 1.4.

The order of the bases is important along the length of the DNA, and each sequence of three bases, called a *triplet*, represents the words in the genetic code. Each triplet codes for an amino acid so that AAA is lysine and UGU is cystine, with signals for ‘stop’, such as UGA, and ‘start’ (no simple sequence but TATA is a reasonable example) to establish the beginning of a gene. More triplets are used to code for each of the 20

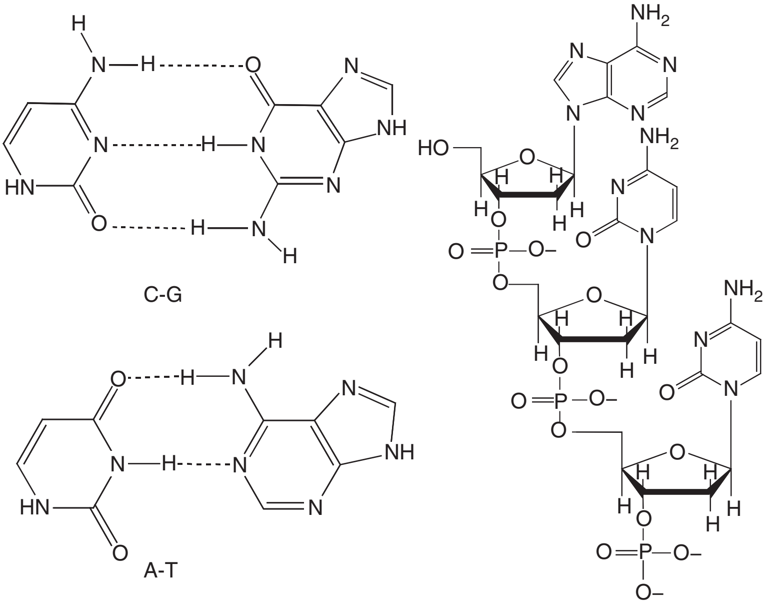

Figure 1.4 Watson–Crick DNA base pairs, and the DNA backbone used by every life form on Earth (except some RNA viruses) for genetic information.

or so amino acids used in living organisms and the order in which they must be put together to form a protein (Figure 1.5). The information coded within the DNA is propagated from generation to generation nearly always correctly, but sometimes with mistakes or mutations. Not all mistakes are bad; mistakes that provide an advantage in the local environment are good mistakes and allow evolution. The organism with the good mistake will evolve and adapt better to its surroundings, outgrowing less-well-adapted organisms.

Proteins are constructed from long chains of amino acids linked together by a peptide bond. There are 20 common amino acids that are coded within the genome, and they are all of L-optical activity. *Optical activity* refers to the interaction of molecules with polarised light and divides molecules into three types: those that do not rotate the plane of polarisation of the light, those that rotate the plane of polarisation to the right, and those that rotate the plane of polarisation to the left. The two types of molecules that rotate light are called *chiral* molecules, and those that do not are called *achiral*. The choice of one set of chiral molecules, called *homochirality*, over the other set is a marker for biological activity. Although amino acids may be produced in space on the ice mantles of interstellar dust grains, they are thought to be racaemic mixtures, meaning that they have equal quantities of the L and D forms of the chiral molecules. Similar optical purity is seen in the bases of DNA

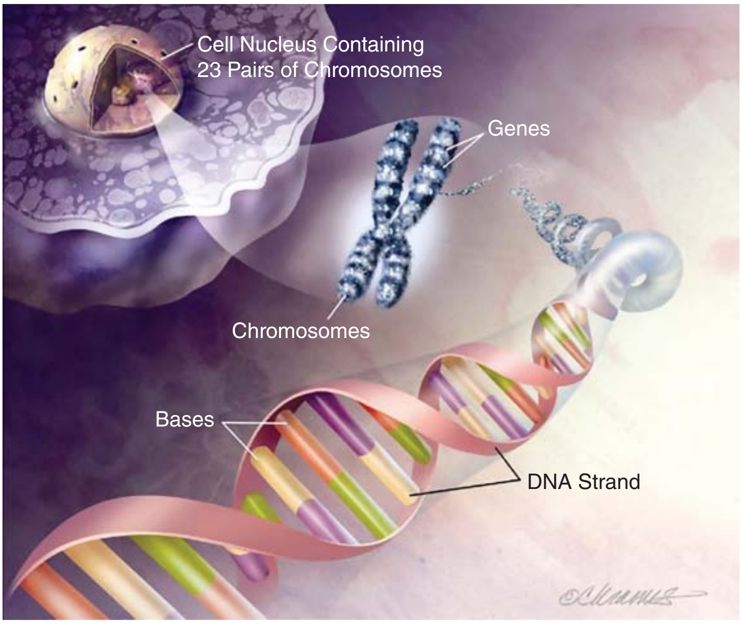

Figure 1.5 The genetic code. Source: Reproduced from *Alzheimer's Disease Education* by courtesy of the National Institute on Aging.

and RNA and with biologically active sugars. Curiously, all sugars are D-enantiomers.

The origin of homochirality is not known [7]. There is a tiny energy difference between the optical isomers associated with a 'parity violating energy difference' of order 10^{-15}–10^{-17} J, but in general homochirality will require biological amplification favouring one enantiomer over another, i.e. *enantiomeric amplification*. It has been suggested recently that organic synthesis in the circularly polarised light field around a star in the interstellar medium or due to chiral-specific surface reactions may also provide a mechanism for enantiomeric amplification, and we shall discuss this later. Homochirality is, however, easily achieved by biological systems and may be considered as a *biomarker* – a marker for the existence of life.

It is the variety of life around the edges of the biosphere on Earth that is a testimony to its adaptation and ability to survive in harsh and extreme environments. The bacteria in the hot-water spring shown in Figure 1.6 have adapted to different temperatures and salinities [8–11]. Some bacteria require extreme temperatures, e.g. hyperthermophile organisms require hot water and will not survive below 90 °C. The extremophile bacteria are from a general class of organisms that have adapted and thrive in extreme living conditions found in deep-sea marine environments and deep subsurface colonies. These bacteria may make up most of the collection of biological organisms