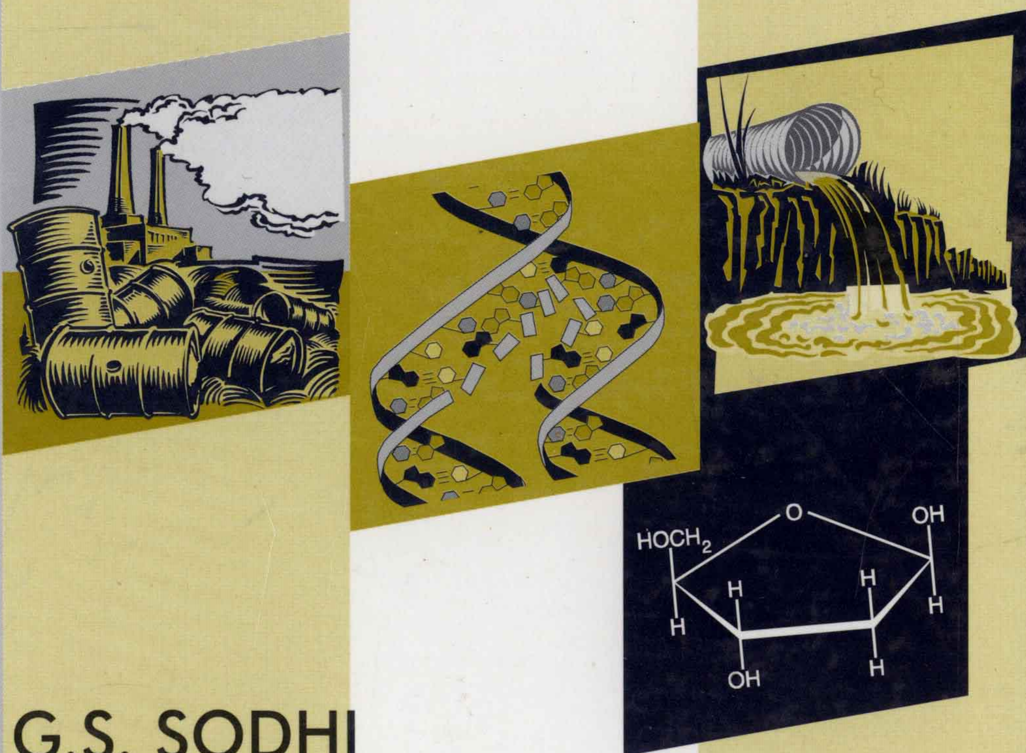
FUNDAMENTAL CONCEPTS OF ENVIRONMENTAL CHEMISTRY



G.S. SODHI

Alpha Science

Fundamental Concepts of ENVIRONMENTAL CHEMISTRY

G.S. Sodhi

Alpha Science International Ltd.

G.S. Sodhi (M. Phil., Ph.D.)
Department of Chemistry, SGTB Khalsa College
University of Delhi, Delhi-110 007, India

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Preface

The term *Environmental Chemistry* has come to be regarded as synonymous with environmental pollution. Many conventional texts stick to this narrow definition and highlight only the problem of pollution resulting from the varied uses of chemicals. Yet it must be emphasised that environmental chemistry deals with a wider aspect of knowledge. The problem of pollution is just a small segment of this discipline.

A broader interpretation of the chemistry of the environment predates the pollution problem; it predates even the origin of universe. It initiates with the emergence of small atoms and molecules—the simplest chemical entities—and their organisation through various geochemical and geophysical processes into planets, including our earth. It then explains the evolution of earth's atmosphere and hydrosphere.

The hydrosphere provided a medium for the biochemical transformation of some of the simple chemical entities into molecules of life. With the emergence of life, each living species extracted a niche for itself. The habitat was gradually modified and thus emerged the biosphere.

Right from the time the man made the earth his home, he has tried to follow the hedonistic doctrine, that is, he has treated avoidance of pain and achievement of pleasure as the highest aim of mankind. In pursuit of this aim he developed a wide range of energy resources. The easy access to energy paved the way for modern methods of industrial and agricultural production.

The application of energy resources no doubt provided comfort and happiness to man, but it also started degrading his habitat. It was then that the problem of air and water pollution cropped up. It soon became apparent that the contamination of natural environment threatened the very existence of mankind. The hedonistic principle, therefore, demanded measures to check further ecological degradation so as to conserve the environment. Since then the philosophy of environmental conservation has come to stay with mankind.

It is in this broad perspective that this book is written.

G.S. SODHI

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Abiotic Origin

CHAPTER 1

Atoms and Molecules

Believe it or not, all naturally occurring elements which are the building blocks for all forms of matter, both the living and the nonliving, originated in the cores of stars. The study of the origin and build-up of these elements in the stars is called *nucleosynthesis*. The interstellar space was also the site where the first series of molecules were formed. Therefore, these molecules are referred to as *interstellar molecules*. To know more about nucleosynthesis and interstellar molecules, we have to know a great deal more about the origin of the universe.

Origin of the Universe

There are two theories pertaining to the origin of the universe: Static (or the steady state) theory and the evolutionary (or the big-bang) theory. The steady state theory (or the continuous creation hypothesis as is often called) propounds that the universe did not have a beginning in time and that matter is being created on a continuous basis. The big-bang theory, on the other hand, supports the idea that the universe had a beginning in time. It advocates that the universe was created at time t_0, about 10^{10} years ago, when a hyperdense sphere of matter packed into a volume roughly that of our solar system, with extremely high density and temperature, exploded in a 'big-bang' at or near the velocity of light.

How can these two patently divergent views be reconciled? Which of the two theories is more accurate? We do not know; perhaps we shall never know. However, the astronomical evidence is biased in favour of the big-bang hypothesis. We shall, therefore, choose the 'big-bang' as the starting point of our discussion on the origin of the universe.

The Three Eras

The big-bang model divides the history of universe into three eras—radiation era, matter era and the life era. Each era is subdivided into a number of epochs; each epoch corresponds to a specific period in the build-up of the universe. Fig. 1.1 shows the time scale delineation of the three eras and the corresponding epochs.

1. The radiation era

The hyperdense sphere of matter which caused the big-bang was a giant neutron ball consisting of 10^{78} to 10^{79} neutrons. This neutron ball is often referred to as *primordial matter* or "*Ylem*". The temperature of the "Ylem" was about 10^{30} K. The first epoch, the *chaos epoch*, lasted for just 10^{-27} second, during which time the neutrons of the "Ylem" remained stable. Thereafter, the disintegration of neutrons into protons and mesons initiated, and lasted upto about 10^{-3} second. This stage is referred to as the *hardon epoch*. The neutrons, protons and mesons (collectively called hardons) collided with one another and were converted to high energy photons, thus creating a brilliant fireball of radiation. The temperature during the hardon epoch dropped to about 10^{12} K.

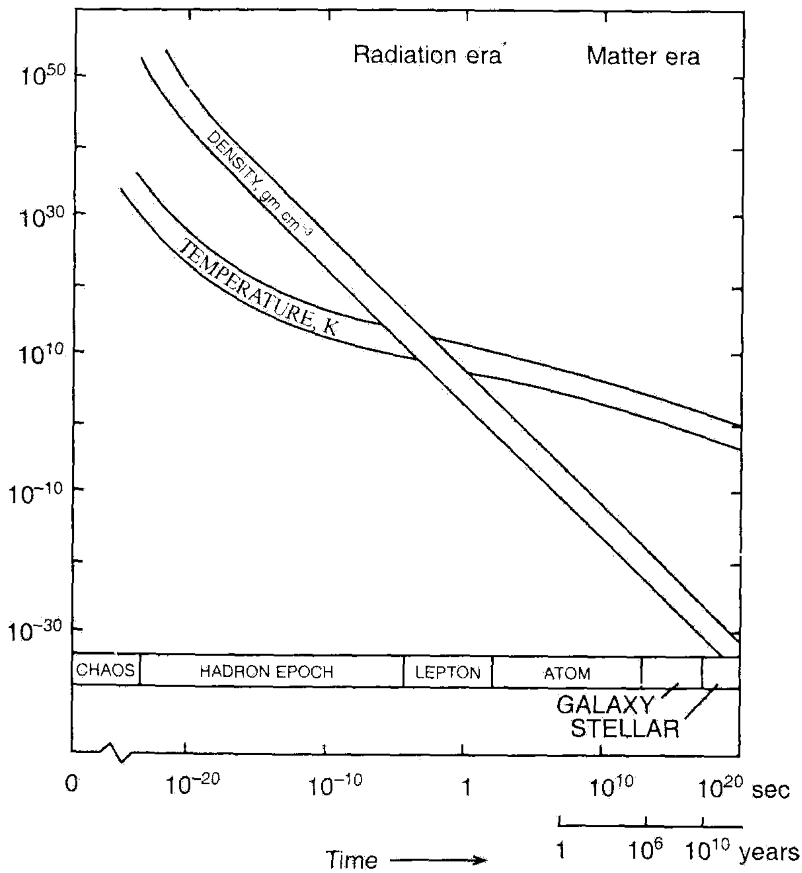

Fig. 1.1 Variation of temperature and density following the big-bang

As the universe expanded, its contents cooled. The average temperature during the third epoch, called the *lepton epoch*, dropped to about 10^{10} K. During this epoch, the lighter elementary particles, such as electrons, neutrinos and muons (collectively called leptons), began to emerge. However, like the hardons, these too were transformed into photons. The lepton epoch lasted upto a few hundred seconds after the big-bang.

During the first three epochs, the radiation density exceeded the matter density by a large amount. Photons of radiation outnumbered particles of matter. As soon as the elementary particles of matter had begun to coagulate, fierce radiation destroyed them. For this reason, the first three epochs are collectively referred to as the radiation era. Whatever matter existed was merely an inconspicuous precipitate suspended in a sea of dense, brilliant radiation.

2. The matter era

The fourth epoch, called the *atom epoch* extended in time from about a few hundred seconds to about a million years after the big-bang. Midway through this epoch, the average temperature had fallen to about 10^6 K. Towards the beginning of the atom epoch, radiation still dominated the matter and the universe remained flooded with photons. However, as the universe expanded the photon density decreased. The early dominance of radiation thus also diminished. Sometime between a few minutes and a million years after the big-bang, the charged elementary particles of matter were able to coagulate electromagnetically without being broken apart by radiation. Henceforth, matter would dominate radiation as the principal constituent of the universe.

The influence of radiation had grown so weak that it could no longer prohibit the combination of those leptons and hardons which had not been transformed into photons. As a result of this combination atoms began to appear. The first to be formed was hydrogen, since it required only a combination of a single electron to a single proton. Significant amounts of hydrogen atoms were synthesized in the early universe.

So long as the temperature of the universe exceeded 10^7 K, fusion of hydrogen atoms resulted in the formation of helium atoms. However, as the temperature dropped below the critical value of 10^7 K, the synthesis of helium, as well as of the higher atomic number elements, ceased. In contrast to the rapid cooling of the early universe, the dense interior of the stars were (and are) suitable for the generation of hotter temperatures and thus of heavier elements. The core of the stars were where the heavier elements were created—and where they are still being created. We shall discuss the plausible mechanisms for the synthesis of these heavy elements in the section on nucleosynthesis.

By the end of the atom epoch, matter was in firm control. During the fifth epoch, the *galaxy epoch,* gravity began to pull some of this matter together into enormous clumps. Galaxies were beginning to form; hot gases, intense radiation and turbulence of the clumps were conducive to galaxy formation. By the middle of the galaxy epoch, the average temperature of the universe had decreased to about 3000 K. The universe was becoming thinner, colder and darker.

The next epoch is the present *stellar epoch*. The dominant episode of this epoch was the formation of stars. As now, the universe has an average density of 10^{-30} g cm^{-3} and an average temperature of 3 K. Under these conditions, the formation of new galaxies is an impossibility. Nevertheless, stars are being formed within the existing galaxies.

The atom epoch, the galaxy epoch and the stellar epoch are collectively termed as the matter era. During this era the matter prevailed, while the radiation subsided. The epochs in the radiation era were spread over a few minutes; the epochs of the matter era were spread over millions of years. The reason being that when the universe was extremely hot, events occurred at a rapid pace; once it cooled, the pace of events slowed down. For example, the formation of stars and their life cycles cover millions and millions of years. During these eons heavy elements have been, and are being, synthesized at a slow pace.

3. The life era

The atoms formed in the universe combined to give molecules. Since these molecules were formed in space, they were termed interstellar molecules. Initially, the interstellar molecules were simple in composition. Gradually, more complex molecules were formed. The increasing complexity of the interstellar molecules with the passage of time is called *chemical evolution*. The chemical evolution finally led to the formation of amino acids and proteins—the molecular building blocks of life.

The life era covers not only the emergence of life on earth, but also the emergence of technologically intelligent life. Technology enables life to control matter, much as matter grew to dominance over radiation, billions of years ago. Matter is now losing its total dominance, at least at those isolated locations where technologically intelligent life persists. The transformation from matter era to life era was not instantaneous. It took millions of years for the matter to dominate over radiation; it took an even greater time for life to dominate over matter. And the transformation is not yet complete—at least when we strive for a more advanced, technologically intelligent life. Hence we name this epoch as the *future epoch*.

Nucleosynthesis

During the atom epoch, the combination of a proton and an electron produced a hydrogen atom. The heavier elements were produced by a series of nuclear reactions which occurred in the cores of stars. The build-up of the elements in the cores of stars is called nucleosynthesis. In order to discuss the role that stars played in the nucleosynthesis, we shall have to describe, qualitatively, the formation and structure of stars.

Life Cycle of a Star

A star is not a static heavenly body. It changes, evolves and dies. The younger stars, such as our sun, are called *Population I stars*, while the older ones are referred to as *Population II stars*. An earlier Population II star was obviously formed when the universe was rich in hydrogen and had small amounts of some lighter atoms like deuterium, helium and lithium. As the condensation of these atoms into the star proceeded, the gravitational potential energy of the atoms was converted into kinetic energy. As a result, a great diffuse mass of gas agglomerated at an accelerated pace, becoming progressively smaller, denser and hotter. Over the next millions of years, the star became compact and spherical and continued to consume hydrogen in various nuclear reactions. When hydrogen was exhausted in the core of the star, the star began to loss energy. To make up for the energy deficit, it contracted under the influence of gravitational forces and became hotter and denser. For the next millenia, the star became optically opaque and began to emit infrared radiation. It continued to lose energy and contract; the density and temperature continued to rise till the star exploded into