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OF GEOCHEMISTRY

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Preface

This book has developed from a course of lectures originally given at Canterbury University College, a constituent college of the University of New Zealand, and later at Indiana University and Columbia University. These lectures have been directed not only at geology students but also at students in other sciences, especially chemistry. The aim has been to summarize the significant facts and ideas concerning the chemistry of the earth and to synthesize these data into a coherent account of the physical and chemical evolution of the earth. Such an aim is fraught with difficulties, difficulties of collecting and evaluating information from many fields, difficulties of interpretation and correlation of apparently unrelated phenomena, and finally difficulties of presentation of the material in a logical manner. The presentation followed in this book is adopted fairly closely from a one-semester course of the same title.

The book begins with a chapter describing the scope and subject matter of geochemistry and giving a brief account of its development. The next chapter deals with the earth as a planet and its relationship to the solar system and universe as a whole and is followed by one discussing the internal structure of the earth and its composition. From the data presented in these two chapters an account is given of the relative abundance of the elements and isotopes, both in the earth and in the universe as a whole, and on the basis of the evidence an attempt is made to present a logical account of the probable pre-geological history of the earth. The aim of these first chapters is to provide a background for the remainder of the book, which is concerned with materials and processes at and near the surface of the earth. Since geochemistry is to a large extent the application of physicochemical principles to processes on and within the earth, some account of these principles is given in the following chapter, with special reference to the chemistry of the solid state. The geochemistry of igneous rocks is then dealt with, followed by a chapter on sedimenta-

tion and sedimentary rocks. The following chapters deal in turn with the geochemistry of the hydrosphere, the atmosphere, and the biosphere. The geochemistry of the hydrosphere is essentially the geochemistry of sea water and poses such fundamental questions as the mode of origin and evolution of the ocean. The geochemistry of the atmosphere is concerned with the nature of the primeval atmosphere and the changes it has undergone through interaction with the hydrosphere, the biosphere, and the lithosphere. The geochemistry of the biosphere involves a discussion of the amount of organic matter, its composition, and the role of organisms in the concentration and deposition of individual elements. Then follows a chapter on metamorphism and metamorphic rocks, and the final chapter is a brief summary and synthesis in terms of the geochemical cycle.

Throughout this book temperatures are expressed in degrees Celsius, unless otherwise stated; tons are metric tons (1000 kg).

The emphasis throughout is on interpretation rather than description, on what is yet to be learned as well as what is already known. It is assumed that the reader is conversant with the fundamental concepts of geology and the principles of physics and chemistry and is familiar with the standard literature on these subjects. Although the book is written primarily from the point of view of a geologist, I hope that it will also be interesting and stimulating to chemists and physicists who are attracted by the fundamental problems of the earth. These problems can be solved only by the combined efforts of workers in many fields. Large gaps exist in our knowledge and understanding, but even a brief survey reveals the lack of perfectly feasible research which could contribute to reducing these gaps—and might also bring out others now unsuspected. There is an urgent need for more precise chemical and physical data on materials of the earth, for which the geologist is dependent on the chemist and the physicist.

This book is necessarily a compilation from many sources, and these sources include not only published books and papers but also correspondence and conversations with many people. I have been greatly helped by discussion of many of the ideas presented in this book with my colleagues. I am especially indebted to Professor J. Verhoogen, who read the manuscript for the first edition, and to Professor G. J. Wasserburg and Professor S. Epstein, who read that for the second edition; their comments and suggestions have been of the greatest value.

Since the literature of geochemistry is extremely scattered, a selected bibliography is appended to each chapter. The choice of these references may appear somewhat capricious; however, the policy has been

to include comprehensive texts, significant recent papers (especially those in journals not usually referred to by geologists), and review articles with comprehensive bibliographies. The abbreviations used for journals and periodicals are those of *Chemical Abstracts*. It is hoped that the reader will thereby be guided to the most useful literature in the field, from which he can proceed to further bibliographic research as the spirit moves him.

In the six years since the first edition of this book was published vigorous research in geochemistry has resulted in a great increase in data and considerable progress in concepts and theories. Particularly noteworthy have been the advances in techniques for age determination of rocks, the keen interest in the nature and composition of the earth's interior (and the study of phase changes at temperatures and pressures previously unattainable in the laboratory), the large amount of work on minor and trace elements in geological materials, and the development of isotope geochemistry. This period has also seen the formation of specialist societies, of which the Geochemical Society, founded in 1955, enrolled nearly 1500 members in its first year. The significance and applications of geochemistry have achieved wide recognition.

Under these circumstances a revision of *Principles of Geochemistry* has become highly desirable. Many of the data in the first edition have been superseded by more reliable figures, and there has been a concomitant development in the theoretical framework of the subject. This revision retains the original organization of the book, but the changes in detail are numerous. The number of tables, and especially of figures, has been considerably increased in order to incorporate more information in a readily comprehended form. The bibliographies accompanying each chapter have been thoroughly revised to include new sources of information and to eliminate other references which have been largely incorporated in the newer works.

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Introduction

The Subject of Geochemistry.   In the simplest terms geochemistry
may be defined as the science concerned with the chemistry of the
earth as a whole and of its component parts.   At one and the same time
it is both more restricted and also more extensive in scope than geology.
Geochemistry deals with the distribution and migration of the chem-
ical elements within the earth in space and in time.   The science of the
occurrence and distribution of the elements in the universe as a whole
is called cosmochemistry.

Clarke, in *The Data of Geochemistry*, defined the subject in a more
restricted form:

Each rock may be regarded, for present purposes, as a chemical system in
which, by various agencies, chemical changes can be brought about.   Every
such change implies a disturbance of equilibrium, with the ultimate formation
of a new system, which, under the new conditions, is itself stable in turn.
The study of these changes is the province of geochemistry.   To deter-
mine what changes are possible, how and when they occur, to observe the
phenomena which attend them, and to note their final results are the func-
tions of the geochemist. . . . From a geological point of view the solid
crust of the earth is the main object of study; and the reactions which
take place in it may be conveniently classified under three heads—first, re-
actions between the essential constituents of the earth itself; second, reac-
tions due to its aqueous envelope; and third, reactions produced by the
agency of the atmosphere.

V. M. Goldschmidt (1954) described geochemistry in the following
terms:

The primary purpose of geochemistry is on the one hand to determine
quantitatively the composition of the earth and its parts, and on the other
to discover the laws which control the distribution of the individual ele-
ments.   To solve these problems the geochemist requires a comprehensive
collection of analytical data on terrestrial material, such as rocks, waters,
and the atmosphere; he also uses analyses of meteorites, astrophysical data
on the composition of other cosmic bodies, and geophysical data on the

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nature of the earth's interior. Much valuable information has also been derived from the laboratory synthesis of minerals and the investigation of their mode of formation and their stability conditions.

The main tasks of geochemistry may be summarized thus:

1. The determination of the relative and absolute abundances of the elements and of the atomic species (isotopes) in the earth.
2. The study of the distribution and migration of the individual elements in the various parts of the earth (the atmosphere, hydrosphere, crust, etc.), and in minerals and rocks, with the object of discovering principles governing this distribution and migration.

The History of Geochemistry. The science of geochemistry has largely developed during the present century; nevertheless, the concept of an autonomous discipline dealing with the chemistry of the earth is an old one, and the term "geochemistry" was introduced by the Swiss chemist Schönbein (discoverer of ozone) in 1838. The first estimates of the abundance of the elements in the earth were made by Döbereiner over a hundred years ago. Such estimates were, of course, little better than intelligent guesses. A good deal of basic data, mainly on the composition of minerals and rocks, had already been acquired by 1850, much of it as a result of the work of Berzelius and his school in Sweden. The first attempt to collate and interpret this data was made by the German geologist and chemist Bischof in his *Lehrbuch der physikalischen und chemischen Geologie*, first published in 1847–1854. This was a standard work for a number of years, being superseded towards the end of the century by Roth's *Allgemeine und chemische Geologie*, published in 1879–1893.

Throughout the nineteenth century geochemical data were mainly the by-product of general geological and mineralogical investigations and comprised more and better analyses of the various units—minerals, rocks, natural waters, and gases—making up the accessible parts of the earth. For many years this work was largely confined to European laboratories, but with the organization of the U. S. Geological Survey and the appointment of F. W. Clarke as Chief Chemist in 1884 a center devoted to the chemical investigation of the earth was founded on the American continent. The geochemical work of the U. S. Geological Survey has grown steadily, until now it is administered as an individual section within the survey; it is probably the largest research organization in the field of geochemistry today.

Clarke was Chief Chemist for 41 years, until he retired in 1925. He was responsible for a vast and ever-growing output of routine analyses of minerals, rocks, and ores collected by the field staff or submitted for

examination, but he was always concerned with the fundamental significance of the mass of factual data thus acquired. His *The Data of Geochemistry*, first published as *U. S. Geological Survey Bulletin* 330 in 1908, passed through five editions in less than twenty years. The latest edition, which appeared in 1924, is still an invaluable source of information, although now decidedly outdated in some parts.

In many respects the appearance of the last edition of *The Data of Geochemistry* in 1924 marks the end of an era. During the preceding hundred years geochemical research was largely synonymous with the analysis of those parts of the earth accessible to visual inspection and chemical assay. From the nature of things it could be little more; interpretative geochemistry, the creation of a philosophy out of the mass of factual information, had to wait upon the development of the fundamental sciences, especially physics and chemistry. A single illustration will serve to demonstrate this: the failure of all attempts to explain adequately the geochemistry of the silicate minerals before the discovery of X-ray diffraction provided a means for the determination of the atomic structure of solids.

The development of geochemistry in new directions was greatly advanced by the establishment of the Geophysical Laboratory by the Carnegie Institution of Washington in 1904. The policy followed in this laboratory of careful experimentation under controlled conditions, and the application of the principles of physical chemistry to geological processes, was an immense step forward. Previously geologists and chemists had been skeptical of the possibility of applying the techniques and principles of physics and chemistry to materials and processes as complex as those on and within the earth.

At the same time the original staff of the Geophysical Laboratory was beginning work in Washington, a new school of geochemistry was growing up in Norway. Fathered by J. H. L. Vogt and W. C. Brøgger, it attained world-wide distinction through the work of V. M. Goldschmidt and his associates. Goldschmidt graduated from the University of Oslo in 1911, and his doctor's thesis, *Die Kontaktmetamorphose im Kristianiagebiet*, was a basic contribution to geochemistry. It applied the phase rule, recently codified by the work of Bakhuis Roozeboom, to the mineralogical changes induced by contact metamorphism in shales, marls, and limestones, and it showed that these changes could be interpreted in terms of the principles of chemical equilibrium. During the next ten years his work was devoted largely to similar studies on rock metamorphism. These studies stimulated related research in other Scandinavian countries and led eventually to

the enunciation of the principle of "mineral facies" by Eskola in a paper published from Goldschmidt's laboratory.

In many ways 1912 can be considered a critical date in the development of geochemistry. In that year von Laue showed that the regular arrangement of atoms in crystals acts as a diffraction grating towards X rays, and thus made the discovery that enabled the atomic structure of solid substances to be determined. Since the geochemist is largely concerned with the chemistry of solids, the significance of this discovery can hardly be overestimated. However, some years elapsed before the impact of this new development was felt in geochemistry. In the last edition of *The Data of Geochemistry*, published in 1924, no mention is made of it. It is a tribute to Goldschmidt's insight that he not only realized the significance of crystal structure determinations for geochemistry, but also devised a plan of research which led to a maximum of results in a minimum of time. Between 1922 and 1926 he and his associates in the University of Oslo worked out the structures of many compounds and thereby established the extensive basis on which to found general laws governing the distribution of elements in crystalline substances. The results were published in a series of papers entitled *Geochemische Verteilungsgesetze der Elemente*, which in spite of the title dealt largely with the crystal structures of inorganic compounds. In these publications Goldschmidt's name is associated with T. Barth, W. H. Zachariasen, L. Thomassen, G. Lunde, I. Oftedahl, and others, all of whom have since had notable careers.

In 1929 Goldschmidt left Oslo for Göttingen, where he began investigations on the geochemistry of the individual elements, applying the principles discovered in the previous years and making use of the current development in quantitative spectrographic methods for rapidly determining small amounts of many elements with a high degree of precision. The results are well summarized in the seventh Hugo Müller lecture of the Chemical Society of London "The principles of distribution of chemical elements in minerals and rocks" (1937). Because of conditions in Germany Goldschmidt returned to Oslo in 1935. Unfortunately, after the German invasion of Norway in 1940 he was able to do little more work. He was forced to flee Norway in 1942 to avoid deportation to Poland, and escaped to Sweden and thence to England. His health was seriously affected as a result of imprisonment in concentration camps in Norway, and he never recovered, dying in 1947 at the comparatively early age of 59.

Thanks largely to the work and the stimulus of Goldschmidt, the last thirty years has seen geochemistry develop from a somewhat incoherent collection of factual data to a philosophical science based

on the concept of the geochemical cycle in which the individual ele-
ments play their part according to established principles. Geochemical
speculation has extended beyond the accessible parts of the earth to
the nature and constitution of the interior, the development of the
earth throughout geological time, and ultimately to its pregeological
history and to the history of the solar system as a whole.

An important school of geochemistry has developed in Russia, espe-
cially since 1917. Its greatest names have been V. I. Vernadsky and
his younger colleague A. E. Fersman. Its productivity has been im-
mense, including a very large work on geochemistry by Fersman,
published in four volumes between 1933 and 1939. Unfortunately,
practically all this literature is in Russian, and its availability, never
wide, has become increasingly circumscribed in recent years. Geo-
chemistry in Russia has been particularly directed towards the search
for and exploitation of mineral raw materials, evidently with consid-
erable success.

The Literature of Geochemistry. Geochemical facts, theories, and
fantasies are widely scattered throughout the scientific literature. The
first source of such data is naturally geological publications, but their
number is legion and geochemical papers may be found in any of
them. Chemical publications contain, of course, much that has geo-
chemical significance, and occasionally classical material appears
therein, as, for example, the symposium entitled "The physical chem-
istry of igneous rock formation," published by the Faraday Society
in 1925. Fortunately, the chemical literature is relatively accessible
through abstract journals. The literature of astronomy, biology, and
of physics also carries information of importance to the geochemist.
Until recently there was no journal specifically for geochemistry (the
German periodical *Chemie der Erde* deals mainly with petrology and
mineralogy); this situation has been remedied by the appearance of
Geochimica et Cosmochimica Acta, a periodical published in England
under the direction of an international board of editors. Although
this journal attracts many specifically geochemical papers, many data
of significance for geochemistry continue to appear as incidental ma-
terial in publications concerned with mineralogy, petrology, economic
geology, inorganic and physical chemistry, and other sciences.

Three outstanding books are standard reference works in the field
of geochemistry. One is the 1924 edition of Clarke's *The Data of
Geochemistry*. It is still the finest and most readily available collec-
tion of analytical data on geological material and on this account
alone is an essential work. In addition, it documents excellently an
enormous mass of literature, much of which still has significance. The

second is *Geochemistry* by Rankama and Sahama, published in 1950. This authoritative and up-to-date book not only treats the general aspects of the subject, but also gives a detailed account of the geochemistry of each element. The third is *Geochemistry* by V. M. Goldschmidt. Goldschmidt had prepared a great deal of manuscript for this work when he died in 1947, and thanks to the conscientious editorial work of Dr. A. Muir, and contributions to missing sections by other people, it was finally published in 1954. While similar in scope to the book of Rankama and Sahama, it bears the distinctive stamp of Goldschmidt's genius for arriving at broad generalizations which correlate a large number of unconnected observations.

Selected References

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GREEN, J. (1953). Geochemical table of the elements for 1953. *Bull. Geol. Soc. Amer.* 64, 1001–1012. This is a very useful compilation of up-to-date geochemical data, compactly presented on a large periodic table.

RANKAMA, K., and TH. G. SAHAMA (1950). *Geochemistry.* 912 pp. University of Chicago Press, Chicago.

The Earth in Relation to the Universe

The Nature of the Universe. The earth is a unit within the solar system, which consists of the sun, the planets and their satellites, the asteroids, the comets, and the meteorites. The sun itself is only one star within our galaxy, which comprises probably more than 10^{11} stars and has a lens-like form with a diameter of about 70,000 light-years (1 light-year $\backsimeq 10^{13}$ km). Beyond our own galaxy there is a very large number of other systems of stars of approximately the same size. These systems, the extragalactic nebulae, are scattered fairly uniformly through space, the nearest to us being the Andromeda nebula at a distance of about 1,000,000 light-years. The spectra of these extragalactic nebulae show a displacement of the lines towards the red end of the spectrum, this red shift being approximately proportional to their distance. The red shift is regarded as a Doppler effect due to recession of the nebulae with velocities approximately proportional to their distance, and leads to the picture of an expanding universe. A large part of the theory of the expanding universe is still highly speculative; for this reason conclusions based on the theory also partake of its speculative character.

The Age of the Universe. The theory of an expanding, dynamic universe implies that the universe has been and is in a state of evolution. If we extrapolate backward in time we arrive at a state when the universe was "contracted to a point," or when all the matter in the universe was concentrated into a very small region. It is customary to regard this as its primitive state and to reckon the astronomical age of the universe from this epoch. With certain assumptions as to the rate of expansion the astronomical age of the universe is computed to be about 5×10^9 years.

A different and independent view of the age of the universe is provided by the concept of the age of the elements. The underlying assumption here is that the elements were all formed at approximately

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the same time (the zero point of this time scale) and that the primitive constitution was subsequently modified by radioactivity and thermo-nuclear reactions. The age of the elements is then reckoned from the time when the naturally radioactive series consisted entirely of the parent elements (non-radiogenic "daughter" elements may have been present). The natural radioactive series of importance for this dating are given in Table 1.

TABLE 1. SOME NATURAL RADIOACTIVE SERIES OF SIGNIFICANCE FOR GEOLOGICAL DATING

Parent elements	Total half-lives	End products
U^{238}	4.5×10^9 years	$Pb^{206} + 8He^4$
U^{235}	7.1×10^8 years	$Pb^{207} + 7He^4$
Th^{232}	1.5×10^{10} years	$Pb^{208} + 6He^4$
Rb^{87}	5.0×10^{10} years	Sr^{87}
K^{40}	1.3×10^9 years	A^{40}, Ca^{40}

Data on the abundances of the elements have shown that those of atomic number greater than 40 are of approximately equal abundance, indicating that, whatever the process of formation, nuclei of approxi-mately the same complexity were formed in approximately equal amounts. Since the abundance of U^{238}, with a half-life of 4.5×10^9 years, is about the same as that of the stable elements bismuth and mercury, the elements cannot have formed more than a few thousand million years ago, as otherwise U^{238} would have largely disappeared through disintegration. On the other hand, the low abundance of the naturally radioactive potassium isotope, K^{40}, with a mean half-life of 1.3×10^9 years, indicates that the formation of this nucleus occurred at least a few thousand million years ago, giving it sufficient time to decay to a large extent. Similar reasoning explains the almost com-plete absence of Np^{237} and Pu^{239}, whose half-lives are 2.25×10^6 and 2.4×10^4 years. An independent solution is provided by considera-tion of the relative abundances of U^{235} and U^{238}. If these two isotopes were originally formed in approximately equal amounts, the present ratio of U^{235} to U^{238} (1:140) is due to the shorter life of U^{235}, which causes it to disappear much more rapidly than U^{238}. The half-life of U^{235} is 7.1×10^8 years; hence to reduce its amount to $\frac{1}{140}$ that of U^{238} would take about 5×10^9 years. Evidence of this sort, although qualified by uncertainties in the primordial abundances of the elements, indicates that a unique value can be assigned to the age of the elements.

This age agrees in order of magnitude with the astronomical age of the universe, and suggests that the beginning of expansion and the formation of the elements were interconnected.

Other arguments also support the view that the universe as we know it dates from a few thousand million years ago. Thus, of the isotopes of lead (Pb^{204}, Pb^{206}, Pb^{207}, Pb^{208}), Pb^{204} is not of radioactive origin, and its amount should be the same now as when it was originally formed; the other isotopes are presumably partly original and partly derived from the decay of U^{238}, U^{235}, and Th^{232}. In material containing both uranium and lead the isotopic composition of the lead has undergone a progressive change during geological time; the relative amounts of the radiogenic isotopes have increased with respect to the non-radiogenic Pb^{204}. Meteorites provide us with a particularly satisfactory illustration of this fact. Iron meteorites contain no uranium, and the small amount of lead present has the highest relative amount of Pb^{204} of any natural material. Stony meteorites contain measurable amounts of uranium, and the lead present shows the effect of the continual addition of radiogenic lead in much higher Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios than those for lead extracted from iron meteorites. A mathematical analysis of the data gives an age for meteorites of 4.5×10^9 years, which has been independently confirmed by potassium-argon age determinations on stony meteorites. This is the time since the parent body of meteorites solidified, and it probably can be equated with the age of the solar system.

Another approach to this general problem of the age of the universe is provided by a consideration of the age of terrestrial materials. The change in the isotopic composition of lead with time has been investigated in lead ores of known geological ages; as predicted, it has been shown that Pb^{204} is progressively less abundant in relation to the other lead isotopes in ores of progressively younger age. A statistical study of the data provides a number of independent solutions for the time at which the primeval lead began to be modified by the addition of isotopes generated from uranium and thorium. These solutions show a significant concentration of values at about 3.5×10^9 years. Since the data are determined on specimens from the earth's crust, this age is that of the separation of the crust from the mantle. This evidently postdates the appearance of the earth as an individual body in the solar system, which is probably best given by the age of meteorites, viz., 4.5×10^9 years. The significance of this billion-year interval between the age of the earth and the age of the crust is discussed in the next chapter.

The age of 3.5×10^9 years for the final consolidation of the earth's crust is corroborated by the information available from the dating of individual rocks of the crust by one or another of the radioactive decay schemes. The oldest rock so far dated is a granite pebble from a conglomerate in Southern Rhodesia, which gave an age of 3.3×10^9 years by the potassium-argon method. A similar determination on a granite pebble from a conglomerate in the Canadian Shield has given an age of 3.1×10^9 years. Minerals from pegmatites in several areas —the Canadian Shield, Southern Rhodesia, Western Australia—have given ages of about 2.7×10^9 years, concordant results having been obtained by the uranium-lead, strontium-rubidium, and potassium-argon methods. The time of formation of the primordial crust and the age of the earth as an individual body must of course be greater than these dates.

The Origin of the Universe. In its primitive state, before expansion began, the universe presumably occupied a comparatively small space. In this small space all the matter in the universe was then confined. Under such conditions the internal pressure would be very high, and the temperature very high also. Elements as such would not exist, and the state of matter is visualized as being a tightly packed fluid consisting essentially of neutrons. Most theories attempt to describe the development of the universe from this primitive state. The beginning of expansion and the formation of the elements are regarded as connected processes, the expansion and the consequent cooling providing the conditions under which the elements could be formed. After expansion began, condensation around centers of turbulence in the expanding material gave rise to aggregations of matter which became galaxies and individual stars.

The Nature of the Solar System. In the study of geochemistry the solar system is of primary importance, although it is inconspicuous within our own galaxy and insignificant in relation to the universe as a whole. Data on the solar system are given in Table 2. Any satisfactory theory of the origin of the solar system must explain its regularities, the most important of which are the following:

1. The sun contains over 99.8% of the mass of the system.

2. The planets all revolve in the same direction around the sun in elliptical orbits, and these orbits all lie in practically the same plane.

3. The planets themselves rotate about their axes in the same direction as their direction of revolution around the sun (except Uranus, which has retrograde rotation); most of their satellites also revolve in the same direction.

TABLE 2. DATA ON THE SOLAR SYSTEM

	Sun	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mass (Earth = 1)	332,000	0.05	0.81	1.00	0.11	318	95	14.6	1.3	0.03?
Radius (in kilometers)	695,000	2500	6200	6371	3400	71,000	57,000	25,800	22,300	2900
Volume (Earth = 1)	1,300,000	0.06	0.92	1.00	0.15	1312	734	64	43	0.1
Density	1.41	5.1	5.0	5.52	3.9	1.33	0.71	1.27	2.22	2?
Maximum surface temperature	5500	350	60	60	30	−138	−153	−184	−200	−220
Gases in atmosphere *	Many	None	CO_2	Many	CO_2, H_2O	CH_4, NH_3	CH_4, NH_3	CH_4	CH_4	?

* Nitrogen, hydrogen, and helium are probably abundant in the atmospheres of the larger planets, although undetectable by present methods.

4. The planets show a rather regular spacing as expressed by Bode's law,[1] and they form two contrasted groups: an inner group of small planets (Mercury, Venus, Earth, and Mars), which are called the terrestrial planets, and an outer group of large planets (Jupiter, Saturn, Uranus, and Neptune), which are called the major planets.

5. The major part of the angular momentum of the solar system is concentrated in the planets, not in the sun, in spite of the concentration of mass in the sun.

The Origin of the Solar System. To be acceptable, any theory of the origin of the solar system must account for these regularities. Two main schools of thought exist, both with ancient and respectable antecedents. Both consider the solar system as derived from an ancestral sun or solar nebula. They differ essentially in that one prescribes the action of an external force to form the planets from the sun, whereas the other rejects the idea of an external force and finds the energy required to form the planets within an ancestral solar nebula. The first school of thought dates back to the French philosopher Buffon in 1749, who suggested that the planets were torn from the body of the sun by a collision with another star. The other originated with the speculations of Kant in 1755. Kant visualized the original state of the sun as a rotating tenuous mass of gas occupying the entire volume of the present solar system, from which contraction, accompanied by increasing rotational speed, led to the disengaging of a series of gaseous rings by centrifugal force, these rings then condensing to form the planets. Similar ideas were put forward independently by Laplace and published in his book *Exposition du système du monde* in 1796.

The Kant-Laplace hypothesis held the field for some sixty years, until the physicist Clerk Maxwell showed that the physics of the solar system is inconsistent with the mode of origin postulated by

[1] Bode's law is an empirical series which closely approximates the relative distances of the planets from the sun and can be formulated as follows:

Mercury	Venus	Earth	Mars	(Vacant)	Jupiter	Saturn	Uranus	Neptune	Pluto
4	4	4	4	4	4	4	4		4
0	3	6	12	24	48	96	192		384
–	–	—	—	—	—	—	—		—
4	7	10	16	28	52	100	196		388

Actual distances of the planets from the sun in terms of the Earth's distance as 10

Mercury	Venus	Earth	Mars	(Vacant)	Jupiter	Saturn	Uranus	Neptune	Pluto
3.9	7.2	10	15.2	..	52	95	192	301	395

The law thus gives a good agreement with the measured distances, except for Neptune; the gap between Mars and Jupiter is occupied by the asteroids, at a mean distance of 29.