PHYSICS AND GEOLOGY

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Preface

This book is an outgrowth of courses on the physics of the earth given by the authors over the past decade to senior undergraduates and graduate students in the Department of Physics and the Department of Geology at the University of Toronto. As a consequence the book has two aims:

1. To give students of geology an introduction to the physics of the earth
2. To give scientists in other fields some knowledge of geology and its relation to geophysics

In the authors' view the earth should be regarded as an active body the physiology as well as the anatomy of which can be studied. In the past, geology has been chiefly concerned with describing the part of the earth's surface exposed above the sea and with tracing the earth's later history as indexed by fossils. Methods developed and applied during the past few years, however, have made it possible to describe the whole earth, from its deep interior to its outer atmosphere. Its development has been put into better perspective on an absolute time scale and it has been possible to suggest the physical nature and causes of some of its processes. It is this broader picture of terrestrial behavior which the authors have tried to sketch, blending the older outlines of geology with the newer colors of physics.

Although all three authors were working together in the physics laboratories of the University of Toronto at the time that the book was written, their backgrounds are such that, in preparing the draft manuscript, the responsibilities were divided. Apart from their common bond as physicists, Wilson brings the additional training of a geologist, Jacobs of a mathematician, and Russell of a chemist. However, the work was so divided and the parts so extensively rewritten that no chapter can be said to be the sole responsibility of any one author. Naturally there has had to be selection in so broad a field as the physics of the earth, and the choice of subjects covered reflects to some extent the interests of the authors in their various fields of research.

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CHAPTER 1

The Universe and the Solar System

1-1. Introduction

Before discussing in detail any particular aspect of the surface features or interior constitution of the earth, it is well to consider it first in its proper setting as a member of the solar system. Sooner or later in any discussion of the physical processes which occur within the earth, questions about its origin and early history are bound to arise. These in turn lead to the problem of the origin of the solar system and to other far-reaching astrophysical questions. Such questions are, in their very nature, bound to be extremely controversial, but it is wrong to ignore them, for the answers are important in many matters connected with the later development of the earth. Detailed studies of the thermal history of the earth, for example, depend quite critically on what initial temperatures are chosen. The origin of the earth will therefore be discussed at some length in this chapter; this will help in assessing the validity of particular earth models which will be constructed in later chapters. Before doing so, it will be convenient to introduce some of the terms which will be used by giving a brief account of some of the main features of the earth's surface and interior.

The earth is almost spherical in form, with a diameter of slightly less than 8000 miles. To be more precise and to give figures in the cgs units which will be used throughout this book, the earth has the shape of a spheroid with a mean equatorial radius of 6378.388 km and a polar radius of 6356.912 km. These are the figures adopted internationally. The radius of a sphere having the same volume is 6371.2 km, and a value of

6371 km will be used in any calculation. The earth's mass is 5.975×10^{27} gm, and its average density is just over 5.5 gm/cm^3. The average density of surface rocks, on the other hand, is approximately 2.8 gm/cm^3, so that there must be a density increase toward the earth's center, where the pressure exceeds $3\frac{1}{2}$ million atm. The temperature also increases toward the center. The average value of the surface gradient is about 30°C/km, but this gradient is not maintained at depth. The temperature at the center of the earth is almost certainly less than 10,000°C, and probably is no more than 5000°C.

There are a number of peculiarities about the surface features of the earth. Less than 30 per cent of the earth's surface is land, which is markedly concentrated in the Northern Hemisphere, the oceans being concentrated in the Southern Hemisphere. This contrast is reversed in polar regions. Moreover, 81 per cent of all the land is concentrated in one hemisphere, with its pole in Brittany, the corresponding "water hemisphere" having its pole near New Zealand. There is also a curious antipodal relation between land and sea. Although about 45 per cent of the surface has sea opposite sea, only 1.4 per cent has land opposite land. Whether this arrangement of surface features has existed throughout geological time is an intriguing question, and one on which complete agreement has not yet been reached. (See Secs. 6-6 and 16-4, where polar wandering and continental drift are discussed in some detail.) The oceans hold as many geophysical problems as, or more than the continents do. The greatest ocean depth exceeds the greatest mountain height, and there are mighty mountain ranges on the ocean floor which rival any of the ranges visible on land today.

The topmost layers of the earth are called the *crust.* Its thickness and composition are not constant, but vary between the continental crust, which consists of 30 to 60 km of light rocks (such as gneiss, granodiorite, and granite), and the oceanic crust, made up of dark rocks (such as basalt) usually not more than 5 to 6 km thick. The upper part of the crust is a thin and discontinuous layer of sedimentary rocks and oceanic deposits. That part of the earth between the crust and a depth of approximately 2900 km is called the *mantle,* and for the remaining part—inside the mantle—the word *core* is used. These three main divisions of the earth into the crust, the mantle, and the core are based on seismic evidence which will be discussed more fully in the next chapter.

It should be pointed out that some authors use different terms to denote various subdivisions within the earth. For example, the terms *lithosphere* and *asthenosphere* have been used to indicate outer and inner shells of large and relatively small strength, respectively. Again the terms *sial* and *sima* were introduced before the advent of seismic information about the crust to distinguish, on chemical grounds, between the light rocks of the continents and the dark rocks of the ocean basins. In both cases, *si*lica is the leading constituent, but in the first group the next most abundant constituent is *al*umina, while in the second it is *ma*gnesia. The early geologists recognized that the sima extended beneath the continental blocks, having found intrusions of simatic rock. However, they had no means of distinguishing between the basaltic oceanic crust and the mantle, which is now realized to be formed of denser materials. With increasingly precise knowledge, many of the older concepts and terms are becoming obsolete.

1-2. The Solar System

Until the time of Copernicus (1473–1543) it was generally held that the earth was the center of the universe and that around it revolved the sun, the moon, the planets then known, and the stars. This geocentric theory, or Ptolemaic theory, of the universe became ever more complicated and artificial as it tried to take account of the increasing accuracy of the observations and the newly discovered astronomical phenomena. Copernicus introduced the idea that the sun was the central body around which the earth and the other planets revolved in circular paths. The earth was thus displaced from its position as the center of the universe, being relegated to the status of a mere planet. Indeed the earth is now regarded as the satellite of an undistinguished star in a galaxy which itself is but an ordinary member of an uncountable number of galaxies. The astronomical observations of Galileo (1564–1642), following the invention of the telescope, confirmed the Copernican theory. The researches of Kepler (1571–1630), based on more accurate observations than were available to Copernicus, showed that the planetary orbits were not exactly circular, but elliptical with the sun at a focus. The discovery of the law of universal gravitation by Newton (1643–1727) gave impetus to the theoretical study of planetary motions, and Kepler's laws, which before had seemed distinct and unconnected, were shown to follow as simple deductions from Newton's law. A most sensational achievement was the discovery of a new planet, Neptune, in 1846. Using the discrepancies between the calculated and observed positions of Uranus, Adams (1819–1892) and Le Verrier (1811–1877), independently and unknown to each other, showed that they could be accounted for on the assumption that they were caused by the attraction on Uranus of an unknown planet; moreover, they were able to locate the position of the unknown planet which was in due course observed through the telescope.

The planets fall into two groups, called the inner and outer planets. In order of distance from the sun, the inner planets are Mercury, Venus, Earth, and Mars, while the outer planets are Jupiter, Saturn, Uranus, Neptune, and Pluto. Some information of a general character on the planets is given in Table 1-1, which also includes data on the sun and moon. It can be seen that the four inner planets are small planets, Earth being the largest of the group. With the exception of Pluto, the outer planets are very much larger than the inner ones. Pluto was discovered in 1930, and at present little is known about it. Its diameter is probably intermediate between the diameters of Earth and Mercury.

In 1801 a small planet called Ceres was discovered moving in a path between the orbits of Mars and Jupiter. That was the first of the minor planets to be discovered. There are probably at least 30,000 of them; Ceres, the largest, has a diameter of about 800 km. The orbits of all the minor planets lie essentially between those of Mars and Jupiter, and it has been suggested that the minor planets are the remnants of a major planet which was shattered into fragments at some stage in its history as the result of a powerful disruptive force of attraction during a close encounter with Jupiter. Recently some scientists have questioned this explanation of the formation of the *asteroids*.

Two things about the planetary orbits are of particular interest: (1) all the planets revolve around the sun in the same direction and (2) the orbital planes of the planets with the exception of Pluto differ but little from the plane of the ecliptic. Moreover, the sun, the moon, and the planets all rotate about their axes in the same sense as the direction in which the planets revolve around the sun, with the single exception of Uranus. These very special features must be taken into account when formulating any theory of the origin of the solar system.

By the first quarter of the present century, giant optical telescopes had revealed that the Milky Way system is a collection of some 100,000 million stars in the shape of a lens with the sun toward its rim. The sun's distance from the center of the galaxy has been estimated as 26,000 light yr. The galaxy spins around its center at a rate that would swing the sun completely around it in 200 million yr. The development of large telescopes and spectrographic methods of analyzing light showed that the diffuse and luminous stellar clouds called nebulae are other galaxies beyond our own, each made up of many thousands of millions of stars like the sun. Galaxies tend to be separated in space by distances averaging several times their diameters. They are scattered through all space visible to us with the largest telescopes. The most remote are so distant that light from them takes about 2000 million yr to reach the earth and registers only as faint marks on photographic plates exposed for many hours in the great 200-in. reflecting telescope at Palomar Mountain, California. In the last few years, the invention of another tool, radio astronomy, has made possible the detection of galaxies at even greater distances. Surveys show that galaxies tend to cluster in groups, containing up to a thousand or more. The distribution of clusters is a

TABLE 1-1. CHARACTERISTICS OF THE SOLAR SYSTEM

Characteristic	Mercury	Venus	Earth[a]	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto[b]	Sun
Mean distance from sun (in astronomical units)[c]	0.387	0.723	1.000	[d]	1.524	5.203	9.539	19.18	30.06	39.52	
Inclination of orbit to ecliptic[e] (degrees)	7.0	3.4	0.0	5.1	1.8	1.3	2.5	0.8	1.8	17.1	
Diameter (earth = 1)	0.380	0.961	1.000	0.273	0.523	10.97	9.03	3.73	3.38	0.45	109.1
Mass (earth = 1)	0.0543	0.8136	1.0000	0.0123	0.1069	318.35	95.3	14.54	17.2	0.033?	332,000
Mean density (water = 1)	5.46	5.06	5.52	3.33	4.12	1.35	0.71	1.56	2.47	2?	1.41
Period of axial rotation[f,g]	88^d	30^d?	$23^h56.1^m$	$27^d7.7^h$	$24^h37.4^m$	9^h50^m	10^h02^m	10.8^h	15.8^h	6.4^d?	24.7^d (equatorial)
Sidereal period[h]	88.0^d	224.7^d	365.3^d	27.3^d	687.0^d	11.86^y	29.46^y	84.01^y	164.8^y	248.4^y	
Number of satellites	0	0	1	0	2	12	9	5	2	0	
Mean surface gravity (earth = 1)	0.38	0.88	1.00	0.16	0.39	2.65	1.17	1.05	1.23	0.16?	27.9

[a] The mean radius of the earth is 6371.2 km.

[b] In the above table, Pluto has been listed as a planet. The most recent of G. P. Kuiper's work indicates that it is perhaps an escaped satellite of Neptune.

[c] One astronomical unit is the mean distance from the earth to the sun. It is 93,003,000 miles or 149,642,000 km. The distance from the earth to the moon varies between 252,710 and 221,463 miles (406,610 and 356,334 km).

[d] The mean distance of the moon from the earth is 384,321 km.

[e] The ecliptic is the plane of the earth's orbit about the sun.

[f] Venus has a very dense atmosphere (almost entirely carbon dioxide) which conceals its surface and makes an estimate of its period of rotation exceedingly difficult. Recent work using radio observations indicates that it may be 22^h17^m ($\pm 10^m$).

[g] The sun's period of rotation varies from 24.7^d at its equator to 26.6^d at latitude 35°.

[h] The sidereal period is the time of one revolution with respect to the stars.

problem whose solution is vital to the present conflicting views on the origin of the universe.

1-3. Ages of the Earth and the Universe

The ages of the earth and the universe have always been most intriguing problems. Did the universe originate at some finite time in the past, or has it existed forever? Many of the older cosmologies assume that the universe was created in very much the state in which we find it now; in contrast, some recent theories assume that the universe had no beginning. If the first assumption is correct, it is difficult to account for the observed existence of irreversible processes in nature; the second assumption, on the other hand, fails to account for the continued existence of radioactivity.

That the earth has a finite age was suspected by philosophers long before scientists could support such a view, but now there is a wealth of scientific information bearing on the subject. For example, the rivers of the world are continually contributing sodium salts to the oceans at a rate which can be measured; despite this fact, the amount of salt in the oceans is finite. Separate stages in the evolutionary scale have been recognized and suggest a progressive development of life from some obscure but real beginning. The well-known red shift in the light received from distant nebulae shows that they are rushing away from our galaxy at speeds proportional to their distance. If these motions are real and if they have been going on continuously in the past, then all the matter spread throughout the universe must some time ago have been compressed into a very small compass. This would imply a possible explosive origin for the universe which, assuming that the velocities have not changed throughout time, has been estimated to have occurred some 5500 million yr or more ago.

Modern methods of radioactivity and geochronology have been brought to bear on the problem. The fact that radioactive elements having half-lives of 10^9 to 10^{10} yr exist in nature shows that the age of the earth cannot be much greater than these figures; conversely, the absence of most radioactive isotopes of shorter half-life suggests an age not much less. Ages determined for specific rocks and minerals by measuring the total amount of end product produced by a radioactive parent are as great as 3000 million yr (Chap. 8). Postulated explanations for the variations observed in lead-isotope abundance ratios demand ages for the earth of from 3000 to 5000 million yr. It has also been shown that lead from certain meteorites which contain negligible uranium and thorium could be converted into the lead found in modern rocks by the uranium and thorium in those rocks in a period of some 4500 million yr.

At present there seems to be little doubt that the earth is between 4000 and 5000 million yr old. The figure 4500 million yr is generally accepted and is satisfactory to all branches of science, being probably as accurate as the ages which can be assigned to the times of formation of most minerals and rocks.

1-4. Origin of the Solar System

It must be appreciated that it is by no means certain a priori that the problem of the origin of the solar system can be given a scientific solution. Consider for example a vessel in which the air has been stirred. After some time there remains no clue to the nature or time of the stirring. All memory of the event within the system has been lost.

However, the solar system is not infinitely old and shows some properties that must reflect directly or indirectly its mode of formation. Most evidence indicates that the solar system came into being as the result of some single process, and one is led to enquire whether this was not the basic process of stellar formation. One must also consider the question of whether the solar system just after its formation was essentially the same physically and dynamically as it is today, or whether important evolution took place, after the formation period, some 4000 to 5000 million yr ago. G. P. Kuiper has given good reasons for believing that the planetary masses and compositions have not changed since that time. However, internal rearrangements must have taken place; that is apparent, for example, from the changing features of the earth's crust. Whether such changes are progressive or cyclic is one of the questions on which universal agreement has not been reached. Some of the problems which must be answered are these: Have the continents grown from nuclei during geologic time or have they always been roughly the same size and have they merely been reworked? What is the origin of the hydrosphere? While most evidence favors development from the earth's interior during geologic time, no direct evidence for the evolution of water from the interior has been found. An attempt to answer these and other questions will be made in the following chapters.

Returning to the problem of the origin of the solar system, all that one can do is to attempt to derive its present state from an assumed event or set of circumstances which occurred in the distant past. In a sense the method is one of trial and error. The various processes which have been suggested can be roughly divided into two classes: those which regard the origin as the result of a gradual evolutionary process and those which attribute it to some cataclysmic action—usually associated with the hypothetical encounter of the sun with a star in the distant past. An example of the first type is the nebular theory of Laplace which he published as long ago as 1796, the main features being originally due to Kant (1755). Laplace supposed that far back in time the sun was a rotating, gaseous nebula. Under the general gravitational attraction, the nebula would gradually contract and its rotation would become more rapid. Laplace then supposed that, when the centrifugal force in the outer layers of the nebula exceeded the gravitational attraction of the nebula as a whole, gaseous matter was thrown off, just as mud is thrown off the rim of a rotating wheel when the rotation is sufficiently rapid. The expelled material later formed a ring, like Saturn's ring, revolving in the equatorial plane of the nebula. The nebula continued to contract while the material of the ring slowly collected into a single aggregation of gaseous matter which, on further condensation and cooling, developed into a planet revolving around the central body. As a result of further contraction of the nebula and its increased rotation, additional material was thrown off, to become another planet by the method already described.

Laplace's hypothesis in its original form was generally abandoned at the beginning of the present century. There are two main difficulties in his scheme:

1. J. C. Maxwell (1859) and F. R. Moulton (1900) pointed out that, if the mass of the present planets were spread out along Laplacian rings, such rings could never coalesce into planets. In this respect it is interesting to recall Laplace's appeal to the analogy of Saturn's rings. Research on the stability of the rings by Maxwell showed that, however constituted, they could never be collected into a planet as Laplace supposed.

2. Although the sun has 0.999 of the total mass of the solar system, it possesses less than 0.02 of the angular momentum. Yet as Fouché (1884) and later Moulton (1900) pointed out, one would expect, on the basis of Laplace's hypothesis, that the sun would rotate with its maximum possible angular velocity compatible with stability, namely, about 200 times faster than is actually found.

To answer these difficulties, Moulton and T. C. Chamberlin (1905) proposed a return to a cataclysmic theory of the origin of the solar system such as the collision of the sun with another body, as had been proposed some 200 yr earlier by Buffon. Their ideas were later modified by J. H. Jeans and H. Jeffreys, who attributed the formation of the solar system to the interaction between the sun and a star during a close encounter. Just as the moon by its gravitational attraction raises tides on the earth, so the star raised immense gaseous tides on the sun, and matter was pulled away from the sun, roughly in the direction of the star, to form a long gaseous filament. The filament, being unstable lengthwise, would soon break into several parts, each forming a distinct aggregation of matter, later to develop by cooling and contraction into a planet.

In order to explain how planetary matter was removed from the immediate neighborhood of the sun to the present great distances of the planets and set in motion in nearly circular orbits, H. N. Russell suggested in 1935 that perhaps the sun was at one time not a single star but a binary, and that another star was involved in a close encounter with the sun's companion, causing the results already described. This suggestion raises the problem of the removal from the sun's control of its companion while allowing for the retention of the tidal filament which is supposed later to condense into planets. This difficulty was explained by R. A. Lyttleton in 1936, but even so the binary-star hypothesis is still open to many objections and cannot be accepted. For example, if the planets were all formed at much the same distance from the sun, what process has supervened since then to bring about the immense changes in their distances from the sun as required by their present orbits? Moreover, F. Nölcke (1930) had already shown that a filament of matter drawn out from the sun would rapidly disperse, its density being well below the Roche limit.[1] And further, if the matter had been drawn out of the sun by a near encounter with another star, its temperature must have been more than 1 million °K, and its pressure more than 1 million atm. At 1 million °K the mean velocity of hydrogen atoms exceeds 150 km/sec, and L. Spitzer (1939) showed that the velocity of escape would in fact be reached within a few hours and that the filament would then dissipate. Some of the material would escape into interstellar space; the rest would form an extended gaseous nebula around one or more of the stars involved. These arguments of Nölcke and Spitzer virtually rule out the possibility of a catastrophic origin of the solar system. Lyttleton (1938, 1941) attempted to rescue the theory by supposing that the planets were formed in a two-stage process or that the sun was originally the principal component of a triple system, the other two components being initially close together. However, no plausible explanation can be given of many features of the solar system, and theories of a catastrophic nature have generally been abandoned today.

One is thus led to reconsider the Kant-Laplace hypothesis and in particular the reason for its failure. Any model based on the assumption that the angular momentum and the total mass of the initial solar system have remained unchanged cannot explain the present planetary system. The composition of the planets is so highly selective that the original mass must have greatly exceeded its present value. Advances in astrophysics, particularly in our knowledge of the abundances of the elements, indicate that the composition of the planets is exceptional but that the earth could have formed from matter of approximately solar composition by the loss of most of the gaseous elements. C. V. von Weizsäcker in 1944 returned to the nebular hypothesis. He considered that the sun at some stage in its history passed through a comparatively dense

[1] At the Roche density the self-gravitation of the gas cloud will just balance the solar tidal force. Gravitational stability will exist, and hence planetary condensation will proceed, when the critical density is well exceeded.

interstellar cloud of gas and dust particles. Galactic space is well filled with clouds, known as diffuse nebulae, which are very extensive. If the sun passed into one of them, it would remain within it for hundreds of thousands of years, and owing to its predominant gravitational attraction, it would gather great quantities of nebular material into a vast solar envelope. The envelope would develop slowly as a result of frictional forces into a disklike shape, and it is from condensations in this nebular disk that the planets are supposed to have eventually formed. The mass of the nebula is estimated to have been about one-tenth that of the sun. This much larger mass from which the protoplanets were formed answers the first difficulty of the nebular hypothesis. The second difficulty has been answered by H. Alfvén (1942), who showed that a star could lose angular momentum to an ionized cloud or stellar envelope provided a magnetic field were present.

It is not possible in this book to discuss in detail the breakup of the solar nebula and the formation of the protoplanets. The first attempt, made by von Weizsäcker (1944), was based upon hydrodynamical considerations and was largely qualitative. A modified form of his theory, in which an important role is played by the process of gravitational instability, has been developed by Kuiper (1951), who showed that somewhat less than 1 per cent of the mass of the protoplanets condensed into the planets themselves, the larger planets collecting about 100 times as large a fraction of protoplanetary material as did the smaller ones.

Although Kuiper's theory is today considered most probably the correct one, further mention should be made of the work of Alfvén (1942, 1945, 1954). He assumes that the sun had a general magnetic field and that the gaseous cloud which surrounded it was ionized by radiation from it. The cloud was thus electrically conducting, and Alfvén considers that electromagnetic forces are of prime importance. Whether such forces are negligible or not depends, of course, upon the degree of ionization of the cloud from which the solar system is supposed to derive. Alfvén considers the separation by diffusion of the different constituents of the initial gas cloud which is acted upon by the opposing forces of the sun's gravitational attraction and a magnetic field. The gravitational force acts on the nonionized constituents which are magnetically held. Owing to electromagnetic action, the falling gas clouds become ionized and stopped at certain distances which roughly correspond to the present positions of the planets. Angular momentum is transferred from the sun to the gas clouds by electromagnetic forces, causing a concentration of gas in the equatorial planes. Then through condensation the gas is transformed into small solid or liquid bodies, and the planets formed by the agglomeration of these bodies. One of the main difficulties in the theory is that the postulated magnetic fields are required to exceed certain