A TEXTBOOK ON GEONOMY

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Preface

The past decade has witnessed a spectacular increase in our knowledge of the earth, the solar system (particularly the moon, Mars and Venus), and of the outermost reaches of space itself. This book is concerned primarily with the physics (and chemistry) of the earth. This subject cannot be divorced from the larger question of the origin of the earth and the solar system. Thus the first two chapters are devoted to these broader issues. The manuscript was essentially completed by December 1972 and tries to give an account of our knowledge of the earth up to that time. The subject is developing extremely rapidly, however, and inevitably parts of the text will be out of date by the time the book is published. To keep the length of the book within bounds, some selection of subject matter was necessary—if certain aspects have been discussed in more detail than others, it probably reflects the personal interest of the author rather than its own importance to the general field. It is hoped, however, that a reasonably balanced account has been given. Again because of the vast literature on the subject, many references have had to be omitted—it is hoped none of the more important papers have been overlooked.

I gave much thought to the title of this book. A number of geophysicists have proposed the name 'geonomy' for the branch of planetary science that treats geological and geophysical studies of the solid body of the earth. The book is to some extent broader in scope than the adoption of the proposal might suggest, for it deals in part with broader aspects of planetary science. On the other hand, it is to some extent narrower, for it deals but briefly with the geology of the crust. Nevertheless, I have written the book in the spirit of what its advocates intend the word 'geonomy' to signify, and so have chosen the word in the hope that its use will become more general.

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The Solar System

1.1 Radioactive decay and the age of the earth

The phenomenon of radioactivity was discovered in 1896 by Henri Becquerel. Most naturally occurring elements have isotopes with stable nuclei, although there are several with unstable nuclei. These unstable atoms break down or 'decay' spontaneously, the isotopes which undergo decay becoming, as a result, nuclei of different elements. The fundamental equation of radioactive decay was shown by Rutherford in 1900 to be

$$\frac{dP}{dt} = -\lambda P \tag{1.1}$$

where P is the number of parent atoms at time t, and λ is the decay constant. Integration of equation (1.1) gives

$$P = P_0 \, e^{-\lambda t} \tag{1.2}$$

where P_0 is the number of parent atoms at time $t=0$.

Radioactive decay rates are often expressed in terms of the half-life, $T_{1/2}$, which is the time in which one half of the radioactive nucleus will decay. It follows from equation (1.2) that

$$T_{1/2} = \frac{1}{\lambda} \ln 2 \simeq \frac{0{\cdot}693}{\lambda} \tag{1.3}$$

Solving for t, equation (1.2) gives

$$t = \frac{1}{\lambda} \ln\left(\frac{P_0}{P}\right) = \frac{1}{\lambda} \ln\left(1 + \frac{D}{P}\right) \tag{1.4}$$

where D equals $P_0 - P$, which is equal to the number of daughter atoms at time t.

A radioactive nucleus may decay in a number of ways. It may emit an alpha particle which is the nucleus of an He^4 atom, and thus consists of two protons and two neutrons bound tightly together. In α-decay the daughter product forms the nucleus of a new element whose atomic number is two units less than that of the parent and whose mass number is four units lower. As an example

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + \alpha$$

Another form of radioactive decay is by β-decay, a negative electron being emitted from the unstable parent nucleus. The charge on the nucleus would increase by one, the nuclear mass remaining essentially unchanged.

Another mode of decay is by electron capture. In this process the nucleus captures an orbital electron from the innermost shell (the K shell) and the electron combines with a proton, changing the latter into a neutron. Electron capture thus reduces the atomic number by one unit with no significant change in mass number. The nucleus produced in electron capture may be in an excited state and may then decay to a lower state of energy by emitting the excess energy in the form of a quantum of electromagnetic radiation (a γ ray). Some nuclei may decay in more than one way, one of the most important being K^{40} which decays spontaneously in two ways namely

$$K^{40} + \text{orbital electron} \longrightarrow Ar^{40} + \gamma$$

and

$$K^{40} \longrightarrow Ca^{40} + \beta^-$$

Because of the widespread abundance of 'common' Ca^{40}, only the K^{40}–Ar^{40} branch of the decay is used to any extent in age determinations.

Equation (1.4) depends on two assumptions: that λ is constant, and that the only alteration in amount of daughter or parent in the system is due to radioactive decay. The second assumption that the system has remained closed during its history is often questionable. On the other hand, the energies involved in α- and β-decay are enormous compared with possible external influences, and the assumption that λ is constant is not likely to be in error for these transitions. In the case of electron capture, a very small change in the decay rate of Be^7 (only 0·07 per cent) has been detected in the laboratory by changing the external parameters. The Be^7 electron capture process, however, involves very low energies and it is very unlikely that the decay constant can vary in the case of K^{40}.

For the purposes of age determinations, three criteria must be met by a radioactive isotope: the half-life must be approximately of the order of the age of the earth (4500 m yr); it must be reasonably abundant in terrestrial rocks; and significant enrichments of the daughter product must occur. Table 1.1 gives the half-lives of the commonly used isotopes, and Table 1.2 the abundances of these elements in certain rock types. The dual decay of K^{40} to Ca^{40} and Ar^{40} has already been discussed. Rb^{87} decays to Sr^{87} with the emission of a low energy β-particle. U^{238}, U^{235} and Th^{232} decay through three separate series of radioactive intermediate products to the stable end-products Pb^{206}, Pb^{207} and Pb^{208}, respectively. It follows from equation (1.4) that to obtain an age we have to determine the amounts of the parent and daughter isotopes present in the sample. This is done by means of a mass spectrometer. The experimental details will not be

Table 1.1 Values of half-lives and decay constants

Isotope	$\lambda(10^{-10}\ yr^{-1})$	$T_{1/2}(10^9\ yr)$
K^{40}	$\lambda_e = 0{\cdot}585$	11·8
	$\lambda_\beta = 4{\cdot}72$	1·47
	$\lambda = 5{\cdot}31$	1·31
Rb^{87}	0·147	47·0
	or	or
	0·139	50·0
U^{238}	1·54	4·51
U^{235}	9·72	0·713
Th^{232}	0·499	13·9
Re^{187}	0·161	43·0

(After York and Farquhar (1971))

Table 1.2 Approximate estimates of concentrations of radioactive and 'common daughter' elements in common rocks

	U (p.p.m.)	Th (p.p.m.)	Pb (p.p.m.)	K %	Rb (p.p.m.)	Sr (p.p.m.)
Granite	4	15	20	3·5	200	300
Basalt	1	3	4	0·75	30	470
Ultramafic	0·02	0·08	0·1	0·004	0·5	50
Shale	4	12	20	2·7	140	300

(After York and Farquhar (1971))

discussed here, but a good account of the techniques and interpretation of the results has been given by York and Farquhar (1971).

A minimum age of the earth is given by the age of the oldest terrestrial rocks. Table 1.3 gives evidence for the existence of a continental crust on earth for more than 3000 m yr. Many K–Ar ages have now been reported for stony meteorites ranging from 400 to 5000 m yr. There is, however, a significant preponderance of ages between 4000–4800 m yr. Rb–Sr studies of meteorites show that a major chemical differentiation took place in these bodies some 4300–4700 m yr ago. Lead-isotope analyses also yield an age of 4500 m yr for various meteorite bodies.

Table 1.3 Mineral and whole rock ages greater than 3×10^9 yr

Location	*Method*	*Mineral*	*Age* (10^9 yr)
Kola Peninsula, USSR	K–Ar	Biotite	3·46
Ukraine, USSR	K–Ar	Biotite	3·05
Swaziland	Rb–Sr*	Whole rock	$3{\cdot}07 \pm 0{\cdot}06$
			$3{\cdot}44 \pm 0{\cdot}30$
Transvaal, S. Africa	Rb–Sr*	Whole rock	$3{\cdot}20 \pm 0{\cdot}07$
Congo	Rb–Sr*	Microcline	$3{\cdot}52 \pm 0{\cdot}18$
Minnesota, USA	U–Pb	Zircon	$\gtrsim 3{\cdot}3$
Montana, USA	U–Pb	Zircon	$\gtrsim 3{\cdot}1$

*$\lambda = 1{\cdot}39 \times 10^{-11}\ y^{-1}$.
(After York and Farquhar (1971))

Estimates of the age of the earth may also be made from theories of the evolution of lead-isotope ratios (see York and Farquhar (1971) for a summary of such methods). Table 1.4 gives recent estimates by this method using both meteoritic and terrestrial lead data, and indicates an age of the earth around 4500 m yr. All of these estimates assume that the earth's lead at one time had the same isotopic composition as that now found in iron meteorites.

Table 1.4 Estimates of the age of the earth combining meteoritic and terrestrial lead data

Author	*Age* (10^9 yr)
Patterson, Tilton and Inghram (1955)	4·5
Patterson (1956)	$4{\cdot}55 \pm 0{\cdot}07$
Ostic, Russell and Reynolds (1963)	$4{\cdot}53 \pm 0{\cdot}03$
Tilton and Steiger (1965)	$4{\cdot}75 \pm 0{\cdot}05$
Ulrych (1967)	$4{\cdot}53 \pm 0{\cdot}04$

(After York and Farquhar (1971))

1.2 Composition of stellar and cosmic matter; the origin of the elements

Our knowledge of the chemical composition of the universe is obtained from spectroscopic examination of the radiation from the sun, the stars and interstellar gas, and from direct chemical analysis of lunar samples and meteorites (see Fig. 1.1). Although the abundances of the different elements vary considerably, it may be seen that only ten elements (all with $Z<27$) are quantitatively important, and of these the lightest elements, hydrogen and helium, far outweigh the other eight. With the exception of hydrogen and helium, the chemical composition of the universe is everywhere much the same. Moreover, the abundances of the elements, with certain exceptions, show a rapid exponential decrease with increasing atomic number up to about $Z=30$, followed by an almost constant value for the heavier elements. It is possible that absolute abundances of the elements depend on nuclear rather than chemical properties, and are related to the inherent stability of the nuclei. Terrestrial matter, like meteoritic matter, differs from stellar material chiefly in the rarity of the gaseous elements. This is not surprising and is probably the result of the events which led to the formation of the solar system.

It is believed that the elements were formed in stellar interiors, through processes that involved fusion of hydrogen nuclei and the 'burning' of helium nuclei to form the elements of low mass (deuterium, lithium, beryllium and boron are possible exceptions: they seem to have been produced at lower temperatures by high-energy particle irradiation). These processes, however, are not capable of explaining the existence of elements of higher mass, which require the bombard-

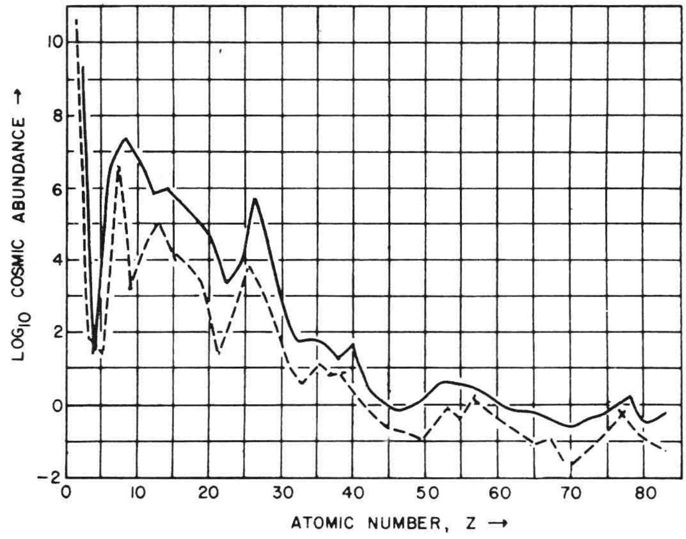

Fig. 1.1 Cosmic abundances of the elements (normalized to 10^6 for Si). The solid lines show elements of even atomic number, and the broken line elements of odd atomic number

ment of the lighter nuclei by neutrons. If the bombardment is sufficiently *slow* (the *s*-process), the elements formed are able to decay between subsequent neutron additions (through β-particle emission) to more stable nuclei. In the *r*-process all neutron additions take place much more *r*apidly before β-decays have a chance to occur. The details of these processes have been thoroughly investigated (see e.g. Fowler and Stephens (1968)). As an example, only the r-process is able to produce transuranic elements.

Equally important as the question of the formation mechanism of the elements is the question of when this formation took place. Some answers to this question have been obtained by radioactive measurements. I^{129} decays through β-emission to Xe^{129} with a half-life of 16·4 m yr. This half-life is so short that no I^{129} now exists in nature. However, this isotope should be produced at the time of formation of the other elements. It can be expected that the condensation of planetary material would incorporate any of the iodine present, but would be unlikely to incorporate much xenon. Xe^{129} formed within the condensed materials would be trapped and might be observed today—very small amounts of excess Xe^{129} have been found in a number of meteorites. Reynolds (1963), who has been foremost amongst those working in this field, has coined the term 'xenology' for the study of xenon isotope abundances in meteorites.

Absolute formation intervals calculated by the Xe^{129}–I^{129} method generally give values between 40 and 300 m yr, depending on the nucleosynthesis model assumed. Variations in relative formation intervals are much less, but are difficult to assess because of different methods of data treatment between different laboratories. Podosek (1970) has subjected all of the Berkeley data to a common method of analysis and found fifteen different meteorites possessing formation intervals within a period of 15 m yr. Nevertheless, real differences existed between some of the samples. The determination of differences in meteorite formation times (or, more precisely, in cooling times) as short as a few million years now appears possible by the Xe^{129}–I^{129} method. When this information is combined with differences in meteorite crystallization times that can now be obtained more precisely by the Rb^{87}–Sr^{87} method (Papanastassiou and Wasserburg (1969)), valuable information can be obtained on the early chronology of the solar system.

Other noble-gas components in meteorites that arise from an extinct radionuclide and have the potential for the determination of formation intervals are the heavy xenon isotopes $Xe^{131-136}$ which arise from the fission of Pu^{244}. These fission Xe components are much more difficult to identify than the excess Xe^{129}, and were not discovered until precise isotopic data were obtained on the calcium-rich achondrites, a class of meteorites high in uranium (supposedly chemically similar to plutonium) and very low in trapped Xe (Rowe and Kuroda (1965)). The Pu^{244}/U^{238} ratio at the time meteorites began retaining xenon not only gives an independent measure of the formation interval of meteorite bodies, but is also important in theories of galactic nucleosynthesis.

Pu^{244} has now been discovered in nature in an old Precambrian rare-earth mineral called bastnaesite from the Mountain Pass deposit, California (Hoffman *et al.* (1971)). Although its existence as an extinct radioactivity had been postulated to explain the Xe isotope ratios observed in meteorites, this is the first indication of its present existence in nature. Pu^{244} has a half-life of about 82 m yr so that the solar system was formed about 60 half-lives ago. The difficulty of finding natural Pu^{244} is that its average concentration should be only $(\frac{1}{2})^{60}$ of its original value, and it could thus only hope to have been found in some mineral in which it was enriched several orders of magnitude. The discovery, if substantiated, has profound cosmological significance. Considered in conjunction with the primeval meteoritic abundance of I^{129}, it can be concluded that about 180 m yr elapsed from the time when a portion of interstellar gas collapsed into the gas cloud that was to form the solar system and the time when the newly formed meteorites were cool enough to retain noble Xe gas. Hoffman *et al.* point out that the present abundance of Pu^{244} due to the influx of Pu^{244} nuclei in cosmic rays may be comparable with, or even greater than, that surviving from primordial earth material. In this respect, Flesicher and Naeser (1972) have found that the Mountain Pass bastnaesite has an apparent Cretaceous fission track age and thus does not reveal any anomalous fission tracks due to Pu^{244}. Further work is necessary on this very important matter.

Blake and Schramm (1973) have suggested the chronological possibilities of the r-only isotope Cm^{247} (half-life $\sim$ 16 m yr). Since I^{129} was present in the early solar system material and I^{129} and Cm^{247} have essentially the same half-lives and both nuclei are produced in the r-process, Cm^{247} should also have been present. Attempts to detect its presence are now being made.

The only nucleo-cosmochronometers established at present are for r-process nucleosynthesis. A short-lived s-process chronometer would be extremely important, since it could provide estimates (independent of any model) of the time interval Δ between the solidification of material in the solar system and the last s-process nucleosynthetic events contributing to the elemental abundances of the solar system. Blake *et al.* (1973) have considered the s-only isotope Pb^{205}, which decays by electron capture to Tl^{205} (with a half-life $\sim$ 15 m yr). Present indications are that Δ for the s-process is comparable to Δ for the r-process, which implies that Δ represents a time scale for the separation of all the solar system material from all nucleosynthetic sources.

The possibility of the p-process isotope Sm^{146} as an extinct natural radionuclide was suggested by Kohman in 1954. Sm^{146} decays to Nd^{142} emitting an α-particle with a half-life of 100 m yr, but the search for an isotopic anomaly in Nd has until recently met with no success. However, Notsu *et al.* (1973) have now obtained the first possible evidence for extinct Sm^{146} in a Ca-rich achondrite ('Juvinas'). It must be pointed out that the formation interval obtained from the decay of Sm^{146} is not necessarily the same as that obtained from the decay of I^{129} or Pu^{244}, since the latter times are produced mainly by the r-process and Sm^{146} by the p-process. Again, the end-point of the formation interval in the case of I^{129}–Xe^{129} or Pu^{144}–Xe is the onset of Xe retention, whereas for Sm^{146}–Nd^{142} the end-point corresponds to the time of the fixation of rare-earth elements in different phases by solidification. An additional potential advantage in studying the Sm–Nd isotope system is the presence of the long-lived radioactive isotope Sm^{147} which could possibly be used for the determination of the solidification age.

1.3 Origin of the solar system

Of all the problems in science, one of the most fascinating is that of the origin and evolution of the solar system. There can be but few scientists who have not at some time speculated on this question. It must be realized, however, that it is by no means certain *a priori* that the problem can be given a definite answer. It may well be that all memory has been lost of the circumstances under which our solar system was born. All that we can do now is to attempt to derive its present state from an assumed event which occurred in the distant past, so that in a sense the method is one of trial and error. It is far more reasonable to assume that planets are normally present in the vicinity of certain stars than to suppose that our planetary system is unique or at least very rare. There are about 200 000 million stars in our galaxy alone. The origin of the solar system is thus part of a very much larger problem–the evolution of the sun and stars in general.

The various theories which have been suggested for the origin of the solar system may be divided into two main classes: those which regard the origin to be the result of a gradual evolutionary process and those which attribute it to some cataclysmic action, usually associated with a hypothetical close encounter of the sun with a star in the distant past. No attempt will be made to trace the historical development of the different theories that have been proposed. Cataclysmic theories are associated with the names of Moulton and Chamberlin at the turn of the century and later with the work of Jeans and Jeffreys. Just as the moon by its gravitational attraction raises tides on the earth, a close encounter of the sun with a star would raise immense gaseous tides on the sun. According to Jeans and Jeffreys, matter would be pulled away from the sun to form a long gaseous filament. This filament would become unstable and soon break up into several parts, each forming a distinct aggregation of matter which would later develop by cooling and contraction into a planet. There are, however, many difficulties with such a theory. Nölcke (1930) showed that a filament of matter drawn out from the sun in such a manner would rapidly disperse, its density being well below the Roche limit.* Furthermore the temperature of the gaseous filament would have exceeded 1 million °K, at which temperature the mean velocity of hydrogen atoms is more than 150 km/s. Spitzer (1939) showed that the escape velocity (see Appendix A) would be reached within a few hours and that the filament would then dissipate. Some of the material would escape into interstellar space while the rest would form an extended gaseous nebula around one or more of the stars involved.

The early evolutionary hypotheses, dating back to Kant in 1755, proved equally unsuccessful. Typical of such theories is the nebular hypothesis of Laplace. Laplace supposed that originally the sun was a rotating, gaseous nebula. Under its general gravitational attraction it would gradually contract, its rotation becoming more rapid. When the centrifugal force in the outer layers of the nebula exceeded the gravitational attraction of the nebula as a whole, gaseous matter would be thrown off, the expelled material forming a ring revolving in the equatorial plane of the nebula. As the nebula continued to contract, 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 described above. It was later shown that if the mass of the present planets were spread out in Laplacian rings, such rings would never coalesce into planets. More important, however, is that one would expect on Laplace's hypothesis that the sun would rotate with its maximum possible angular velocity compatible with stability. In point of fact, although the sun has 0·999 of the total mass of the solar system, it possesses less than 0·02 of the angular momentum. Even if all the angular momentum of the solar system were concentrated in the sun, its period of rotation would be about 12 h and the centrifugal force at its equator would be only about 5 per cent of the force of gravity. Thus rings of matter could not possibly be thrown off in the manner suggested by Laplace.

Such considerations raise the question of whether the solar system just after

* At the Roche density the self-gravitation of the gas cloud would just balance the solar tidal force. Gravitational stability would exist, and hence planetary condensation proceed, when the critical density is well exceeded. For further details see Appendix A.

its formation was essentially the same as it is today or whether significant evolutionary changes have taken place. Any model based on the assumption that the angular momentum and total mass of the solar system have remained unchanged cannot account for present conditions; the composition of the planets is so highly selective that the original mass must have greatly exceeded its present value. The early monistic theories of the origin of the solar system, such as that of Laplace, are almost certainly incorrect but for entirely different reasons from those given historically for their rejection. Additional problems for the earth are the origin of its atmosphere, hydrosphere and continents. Have the continents grown from nuclei during geologic time or have they always been roughly the same size and merely been reworked? This question will be considered in Chapter 8.

The failure of theories of the cataclysmic type to provide a satisfactory explanation for the origin of the solar system led to a reconsideration of those based on the gradual evolution of some primordial system. In all such theories the sun is assumed to be at the centre of a diffuse, gaseous cloud which may have been an interstellar cloud into which the sun had passed, or a gaseous cloud from which the sun had condensed. These new attempts are associated with such names as von Weizsacker, Kuiper, ter Haar and the school of cosmogony that grew up around the Russian astronomer Schmidt.

In all theories of the origin of the solar system up to about 1940 only mechanical (i.e. gravitational) forces were considered. A radical departure from this point of view was made by Alfvén (1942–1945, 1954), who suggested that electromagnetic forces play a key role. In his original theory, Alfvén assumed that the sun had a general magnetic field and that the gaseous cloud which surrounded it was ionized by radiation from the sun. The degree of ionization of any particular element will depend upon temperature and thus upon distance from the sun. The gaseous cloud falls in towards the sun under its gravitational attraction, but the magnetic field around the sun impedes the fall of the ionized constituents. Thus there is a gradual diffusion of the non-ionized constituents through those that are ionized. Any given constituent as it falls towards the sun sooner or later reaches a distance at which, because of its increasing temperature, thermal ionization sets in and the magnetic field begins to act as a brake. Alfvén proposed that four main clouds, differing in composition, were produced by this process. Angular momentum is transferred from the sun to the gas clouds by electromagnetic forces, causing a concentration of gas in the equatorial planes; through condensation the gas is then transformed into small solid or liquid bodies, and the planets formed by the agglomeration of these bodies. The moon and Mars are supposed to condense out of impurities in one cloud (consisting mainly of helium), the earth, Venus and Mercury from another cloud (consisting mainly of hydrogen), the four major planets from a third cloud (consisting mainly of carbon), and Pluto (and perhaps Triton, a satellite of Neptune) from the fourth cloud (consisting mainly of iron and silicon). One of the main difficulties with this theory is that the postulated magnetic fields must be much larger than seem plausible. In particular for the sun, a surface field of 300 000 Γ (gauss) is required, but the field at the present time is less than 2 Γ. In spite of this and other difficulties, Alfvén made a very real contribution to the problem of the origin of the solar system by demonstrating the importance of electromagnetic forces.

Theories of the origin of the solar system considered so far have assumed the formation of the planets to be independent of that of the sun, the planets forming after the sun had become a normal star. Some success (e.g. Hoyle (1955), (1960); McCrae (1960)) has been obtained in recent years starting from a different premise, namely that the origin and formation of the planets are related to the formation of the sun itself. A number of authors have also shown that some of the elements and compounds found in the earth and in meteorites are not compatible with the earth having condensed out of a hot gas cloud of solar composition. In this case the separation of the elements of the earth from the surrounding hydrogen must have taken place at low temperatures.

Most theories of the origin of the planets assume that they accreted from relatively cold homogeneous material. The division of the earth (and possibly the other terrestrial planets) into a crust, mantle and core, has then been presumed to be the result of segregation processes which occurred sometime during or after the accretion of the planet. However, in recent years the possibility that the earth accreted inhomogeneously has been considered. Calculations by Larimer (1967) on the condensation sequence of elements and compounds from the solar nebula led other workers to suggest that the different meteorite classes, the moon and the various regions of the earth represent the accretion of material that has been condensed out of the solar nebula at different temperatures. Clark *et al.* (1972) later suggested that the planets accreted *during* condensation and that internal zoning is an original feature of a planet. They proposed that the iron body that is now the earth's core condensed first and became the nucleus upon which the silicate mantle was later deposited. The last accumulates would be FeS, Fe_3O_4, the volatiles and hydrated silicates. Anderson and Hanks (1972) have examined the condensation sequence in more detail and have shown that earlier difficulties with such a model in accounting for the composition of the moon and explaining how the earth's core became molten may be overcome. The accretion of the earth and formation of the core are discussed in more detail in §§7.3 and 10.5. The ultimate size of a planet will depend on the amount of condensable material available to it in its orbit and the temperature of the nebula in its vicinity before a high temperature phase of the sun, such as T-Tauri, blew the uncondensed and smaller condensed particles out of the inner solar system.

It is beyond the scope of this book to discuss the question of the origin of the solar system in any more detail: some recent reviews have been given by ter Haar (1967); Herczeg (1968); and Williams and Cremin (1968). Meteorites will be considered briefly in §1.6. Because of the great increase in our knowledge of the moon, Mars and Venus following the successful launching of space craft, these three bodies will be discussed separately in Chapter 2. The origin of the solar system remains one of the oldest unsolved problems in natural philosophy. At a meeting organized by the Royal Society of London and the Royal Astronomical