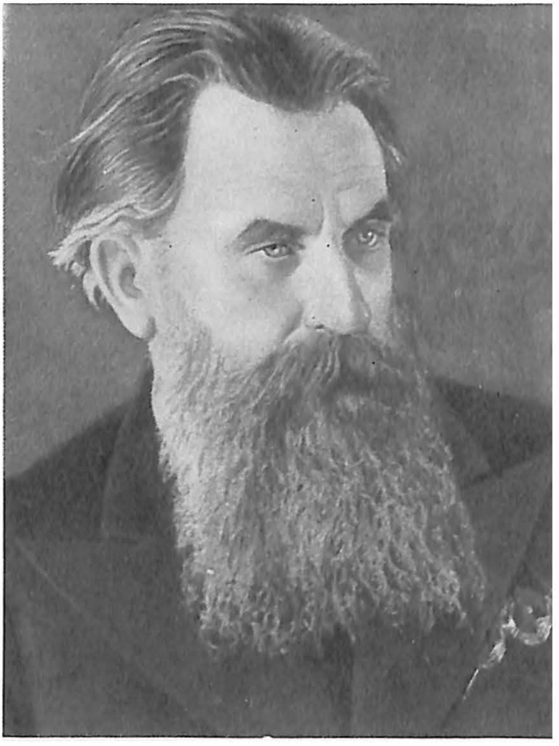
ACADEMICIAN O. SCHMIDT

A THEORY OF EARTH'S ORIGIN

FOUR LECTURES



Academician
OTTO SCHMIDT

A THEORY OF EARTH'S ORIGIN

Four Lectures

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BY GEORGE H. HANNA

О. Ю. ШМИДТ
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PREFACE TO THE THIRD EDITION

During the six years that followed the publication of the Second Edition of this book, Otto J. Schmidt, despite his serious illness, continued to develop his cosmogonic theory, taking advantage of every brief respite the sickness allowed him. In those years he published articles on the origin of asteroids and on the role of solid particles in planet cosmogony; he also prepared some chapters of a capital work on his theory.

His untimely death prevented him from completing his work. He left behind him material for his book and many other manuscripts on various problems as well as working notes and calculations, the majority of which were written between 1951 and 1955.

In a draft foreword for his fundamental work on the theory, Schmidt wrote: "The theory has continually developed and grown richer. In the course of that development, preliminary tentative ideas have gradually been replaced by precise and concrete tenets, gaps have been filled in and the number of phenomena that can be explained by the theory has increased. This development was due to three factors: the appearance of new facts and more profound generalizations in many branches of science, criticism and numerous discussions and, finally, its internal growth, i.e., the further extension of work on the theory. Some erroneous details have now been dropped but, on the whole, the theory proved capable of development and its basic tenets have been proved sound. There can and must be further development and greater precision."

Owing to the considerable development of the theory since the Second Edition of the *Four Lectures* it was not thought advisable to reprint them in their previous form. By making use of articles published by Otto J. Schmidt between 1951 and 1955 and unpublished work, we have been able to follow the author's plan for the revision of the book; the present Third Edition, therefore, reflects the present state of the theory. The addition of new material led to a certain disproportion in the lectures and in the space allotted to the problems they cover.

The sequence of the lectures (2nd and 3rd) has been changed and certain details and calculations relegated to the appendices in accordance with the author's wishes. The bibliography on the Schmidt Cosmogonic Theory and allied problems has been extended.

The present edition was prepared for the press by S. V. Kozlovskaya. In editing the book I was helped by the valuable advice and suggestions of B. Y. Levin, V. S. Safronov and G. F. Hilmy.

A. Lebedinsky

AUTHOR'S PREFACE TO THE SECOND EDITION

The problem of the origin of the Earth is one of such great importance to science that it possesses interest not only for the specialists—astronomers, geophysicists, geologists, geographers and others—but also for the general public. The Soviet people have made very considerable cultural progress so that it is only natural that they should show an interest in this problem and demand an answer from their scientists: the problem of the Earth's origin, say our people, must be solved as quickly as possible on account of its specific importance to the study of nature and from the standpoint of our philosophy of dialectical materialism.

The author's hypothesis of the genesis of the Earth and other planets proposed in 1944 met with a wide response, gave rise to extensive criticism and discussion. In the course of time the hypothesis has developed and grown into a detailed theory. Apart from separate publications in scientific journals it became necessary to publish, at least, an interim report on basic results and methods. The First Edition of this little booklet was published in 1949; it consisted of four lectures which I delivered at the Academy of Sciences Geophysical Institute in 1948.

The preface to the First Edition defined the scope and purpose of the book as follows: the author's purpose is to draw attention to the physical fundamentals and starting point of the theory, for which reason the lectures included only the chief results obtained from the concrete application of the theory; the author tended to avoid details and, when possible, omitted mathematical equations, although the necessary scientific level has been maintained. The Second Edition is the same in character but has been greatly expanded and revised. The theory has continued developing during the two years that have elapsed since the First Edition. The question of the origin of the rotation of the planets about their own axes and the origin of satellites, for example, were first solved in that period. In addition to the new studies undertaken by the author and his colleagues the theory has been developed and applied in a number of papers by other scientists. All this has found its place in the present edition. For the sake of brevity, the section on binary stars that only indirectly related to the chief subject has been omitted.

The author hopes that this Second, enlarged, Edition will make it easier to understand the new theory and will help in its criticism, testing and consequent development.

In revising the material for the Second Edition, the author, as always, relied on the extensive help of the senior scientists of the Geophysical Institute, B. Y. Levin and G. F. Hilmy. The author wishes to express his gratitude to his colleagues.

L e c t u r e 1.

PRESENT STATE OF THE PROBLEM—FORMULATION OF THE PROBLEM—FUNDAMENTAL IDEAS AND FACTS

That the problem of the Earth's genesis is of tremendous importance is axiomatic. From the standpoint of our scientific philosophy it is one of the three most important in natural history, the other two being the origin of life on Earth and the origin of Man. It is one of the cardinal problems for all sciences that deal with the Earth—geology, geophysics and geochemistry. Its significance for biology, in particular to the theory of the genesis of life, is also very great.

In order to understand the present-day regularities in any branch of science, the correct method to be followed is to study those regularities in their historical development, beginning with their first appearance and following their further evolution. Any problem, therefore, be it the problem of the causes leading to the formation of mountains, the cause of terrestrial magnetism or the cause of earthquakes, is, fundamentally, that of when and why mountains began to form or earthquakes first occurred, so that in the final analysis it requires the solution of the problem of the Earth's origin.

The question even arises when practical applications of science have to be made. Practical geology, for example, like all other practical work, is based on certain theoretical views of geological processes which, in turn, depend on conceptions of the origin of the Earth and its early, pre-geological history. Our attempts to find a method for the forecasting of earthquakes must be based on certain views and hypotheses on their causes, that is, on those processes inside the Earth that give rise to them. The causes of those processes must also be examined and this, in the final analysis, brings us back to the cause of causes—the question of the Earth's genesis.

The content of cosmogony, the study of the origin and development of the celestial bodies and their systems, is intimately bound up with the basic questions of philosophy. From the earliest days of science, therefore, cosmogony has been the arena of a fierce ideological struggle. The struggle goes on today, only its form having changed.

A sharp line of demarcation can be drawn between the main philosophies in the very way cosmogonic problems are propounded. Idealist philosophy reduces the problem of the origin of the celestial bodies either overtly or covertly to an act of "creation" or to a statement that it is unknowable (agnosticism). Agnosticism also appears in a hidden form in the profoundly erroneous underestimate of what modern science has at its disposal and the equally fallacious overestimate of what science has not got. This leads to the assumption that the time is not yet ripe to evolve a cosmogonic theory.

However, the abundance of facts that we now possess, including the discovery of a very large number of the objective laws of nature, is sufficient for the solution, in the main, of the question of the Earth's origin.

* * *

At first glance, the history of cosmogony from the 18th century to the present day looks like a mass of unfounded, accidental and fruitless speculations in the sequence of which no development is noticeable. The history of cosmogony is usually given in the form of a catalogue of hypotheses, a very unscientific method. The history of cosmogony has meaning and is instructive when it is seen as a struggle between idealism and materialism that never ceases at any stage in that history. With this approach the materialist line in the development of cosmogony stands out clearly and the whole history of the subject constitutes a useful lesson for modern progressive science. The lessons of the past help us choose that which is positive from the earlier development of science and avoid error.

Let us take a very brief glance at the history of planet cosmogony from that point of view.

Scientific cosmogony begins with the well-known works of Kant (1755) and Laplace (1796). They were the first to propose hypotheses concerning the formation of the solar system out of scattered matter; they regarded it as a regular development of matter that followed the laws of nature and did not need the help of divinity. The tremendous philosophical importance of the work of Kant and Laplace (of which Engels had a very high opinion) lies precisely in this idea of the natural development of matter.

It must be stressed that in the middle of the 18th century, in addition to Kant, the idea of the development of nature was put forward by Mikhail Lomonosov in his brilliant book *On the Strata of the Earth* which has only become widely known of recent years. It will be sufficient to quote the beginning of a well-known statement of his: "Firstly, it must be firmly borne in mind that visible physical bodies on the Earth and the entire universe were not in the same condition as they now are from the time of their creation, but that great changes have taken place in them...."

Kant and Laplace built up their hypotheses on the idea that the Sun and the planets were formed out of dispersed matter. In its general form the idea that big bodies were formed from a "chaos" of tiny particles was known to the Greek materialist philosophers (Democritus). As far as Democritus was concerned, it was only the materialistic conjecture of a genius, but in the hands of Kant and Laplace it became a scientific hypothesis which, in our days, has grown into a scientific theory.

The hypotheses of Kant and Laplace are so well known that there is no need to go into them here. We shall merely stress those features that formed the source of further development. The community of ideas and the similar level of scientific knowledge (18th century) makes the hypotheses of Kant and Laplace so similar to each other that the widely practised merging of them into a Kant-Laplace hypothesis is fully justified. When we speak of the general features we shall also use this term. In modern, especially Soviet, science, the different aspects of the works of Kant and Laplace have had very dissimilar influence and in view of this it will be worth while to discuss their differences.

In the first place, Laplace says straight out that the primeval nebular medium was gaseous in form while Kant employs the less definite term "particles" which we may understand to mean, gas, dust or any other tiny bodies. In this respect Kant's views are broader and lead in a direct line to the modern conception of the protoplanetary matter as gas and dust. The difference is rather great since the presence of dust and other tiny particles in the nebula facilitates the redistribution of energy and the transformation of part of the kinetic energy into heat. As we shall see later it is precisely these processes that are the chief motive forces of evolution.

In the second place, Kant speaks of the gradual cohesion of particles that collide during motion as a condition for their growth, while Laplace's planets are formed from the condensation of gas. Both these lines were later developed further.

In the third place, Kant's hypothesis did not include the separation of "rings" that played such an important part in Laplace's suppositions and was of more interest to his followers than anything else. This was the origin of the "rotation" hypotheses which did not justify their existence.

The shortcomings of the Kant-Laplace hypotheses are well known—their inability to cope with the angular momentum. Kant erroneously imagined that angular momentum was generated in the process of evolution, while Laplace, by assuming it to be present from the very beginning (the rotating nebula), could not explain the paradoxical distribution of the angular momentum between the Sun and the planets and, therefore, ignored it. Laplace's error was discovered in the latter half of the last century (Babinet and Fouché) but cosmogony did not draw the proper conclusions from it for a long time.

The conceptions of Kant and Laplace were limited by the level of scientific knowledge in the 18th century. Not only were immeasurably fewer facts known then than now, but very substantial disciplines in the theoretical sciences had not yet come into being. The law of the conservation of energy and the transformation of one form of energy into another had not entered into our arsenal of scientific equipment and without them modern cosmogony is inconceivable. There were no thermodynamics or statistical physics so that the classics of cosmogony were helpless in the handling of their "particles."

These historically imposed restrictions, amongst which must be included the limitations of philosophy (primitive mechanistic materialism), must not be allowed to overshadow the tremendous significance of the classical cosmogonic hypotheses. Kant and Laplace made a breach in metaphysical philosophy, their hypotheses were built up on the regularities in the structure of the solar system as they were known at that time and provided an explanation for a number of facts; they come close to an understanding of objective reality and the materialist line in the development of cosmogony takes its start from them.

To effect scientific continuity the heritage of the classics should have been developed along materialist lines, abandoning that which was fallacious and incorporating new scientific discoveries. This, however, was not the case. It is true that the idea of evolution found its way into geology and, later, into biology. The conception of an Earth that was fire and molten rocks in the beginning and then gradually cooled off, an idea prompted by volcanic manifestations, came to the fore again in geology and was backed by the authority of Kant and Laplace and supported by the astronomers. In cosmogony itself, however, the ideas of the classics were not developed.

The 19th century was not a creative period in cosmogony. The Laplace hypothesis reigned supreme. Scientific works bore all the marks of adherence to the past. There was hardly any criticism of Laplace and occasional critical notes that did appear (for example, on the disparity between the distribution of mass and the angular momentum which classical cosmogony could not explain) were ignored. Attempts to evolve new hypotheses on the basis of those of Kant and Laplace, such as that of Ligondès, were of no great significance to the development of science.

In the same 19th century that saw such a tremendous development of physics, chemistry, geology and biology cosmogony remained stagnant. There were a few positive achievements dealing with partial problems of cosmogonic significance. Amongst them were the establishment of Roche's limit and, particularly, G. Darwin's development of the theory of tidal forces and tidal friction. These researches have retained their importance although they have frequently been applied incautiously and the role of the tidal theories has been exaggerated.

The stagnation in cosmogony in the 19th century is not to be explained only by the monopoly position held by Laplace's hypothesis. The lag in this particular branch of science is to be explained by its special position in the struggle between science and religion. There was no further development of the materialist line. Such hypotheses appeared as that of the French Academician Faye, a zealous Catholic, who tried to create a pseudo-scientific picture of the formation of the solar system which agreed exactly with the bible story. Similar attempts were made in other countries.

By the beginning of the 20th century the faults in the Kant-Laplace hypothesis had become too obvious. It was rejected for a long time but science was unable to provide anything to replace it that had equal strength and profundity. There came a period of new conjectures, the majority of which had a quite different character, with very obvious traces of agnosticism and subjectivism. Typical of most of these hypotheses was their accidental nature, their sudden flourishing and rapid disappearance.

The appearance of hypotheses is, in itself, a regular feature of the development of science. Friedrich Engels, summing up the whole history of natural science, drew a correct conclusion when he wrote that "the hypothesis is a form of the development of natural science, insofar as it represents thought." Not all hypotheses are alike, however. A genuinely progressive scientific hypothesis is based on the sum total of all known facts and opens the way for the further prognostication and discovery of facts. Many recent hypotheses are built up on isolated facts, subjectively interpreted. Such hypotheses are clearly fruitless and shortlived.

The materialist, in search of objective truth, demands the systematic, consistent and quantitative development of a hypothesis, while a scientist of the idealist school is satisfied with a "generalization of experience" made in the most spectacular way, in the form of a rapidly drawn qualitative picture. The materialist scientist feels it his duty to check his conclusions carefully with the facts and he does not consider his theory complete if there is one single fact that contradicts it; the idealists, it seems, are amazingly indifferent to contradictions. One of them generalizes one group of data from their notorious "experience," while another takes a different group and contradictions do not worry them since there is no objective truth, anyway. This accounts for the tendency for outward effect, carelessness in computations and often enough the absence of even elementary logic.

The work of some contemporary cosmogonists is an extreme expression of this. Some of them use improbable, fantastic data as the starting point on which to build up hypotheses. To this category of hypotheses belongs that of Milne-Haldane, attributing the origin of the planetary system to a collision between a monstrously big quantum and the Sun, or that of Hoyle, according to which the Sun was part of a binary system of which the other component was a supernova that had exploded. Other scientists outspokenly claim a role for the "creator" in the genesis of the celestial bodies. A popular work by W. M. Smart that appeared in Britain in 1951 says without reserve that the solution of problems connected with cosmogony is beyond the bounds of science.

The Jeans hypothesis lasted longer than any of the other 20th century hypotheses. The reason of its popularity was not its scientific value (it had none) and not the undoubted talents of its author but because it was the one most acceptable to the idealist, religious philosophy predominating in bourgeois society.

No wonder the authors of reviews summarizing the level of cosmogony in this period had to reject all existing hypotheses—see the papers of Sir H. Jeffreys, D. ter Haar and W. J. Luyten.

We should be erring, however, if we did not see that the study of natural history must, by its very nature, lead scientists to draw materialist conclusions.

Since the beginning of the forties of this century there has been new interest shown in cosmogony and considerable positive work has been done. Typical of present-day developments in planetary cosmogony is the return to the ideas of Kant and Laplace on the genesis of the planets out of dispersed matter. Some astronomers, however, have taken the liberty of making a number of absolutely arbitrary assumptions.

The hypothesis proposed by the German physicist C. von Weizsäcker was published in 1943 (on account of the Second World War it did not become known in the U.S.S.R. until 1945-46). Chandrasekhar, ter Haar and others supported and tried to develop this hypothesis. Weizsäcker and his followers employed thermodynamics and statistical physics to a greater extent than ever before in cosmogony, an advance on former methods. The starting point of the hypothesis, however, shows its extreme artificiality. To explain the regularities in the distances of the planets from the Sun, Weizsäcker assumes that there were as many vortice zones in the preplanetary cloud as there are great planets. These vortices rotate in a clockwise direction but between them something in the nature of ball bearings is formed; these move counterclockwise and give rise to the planets. Ter Haar attempted to make some corrections in Weizsäcker's work. He rejected Weizsäcker's arbitrary vortice zones and applied the modern theory of turbulence elaborated by A. N. Kolmogorov. G. P. Kuiper made a comparatively successful development of Weizsäcker's ideas but he also added a number of subjective methods that led to a tangle of correct and incorrect theses.

The latest cosmogonic investigations of Kuiper, Urey and Fesenkov regard the solar system as being formed from dust and gaseous matter. A similar primitive state of matter is the basis of the theory that I have been developing since 1943 in collaboration with a group of other scientists; this book is devoted to an outline of that theory.

Our theory can explain the main features of the structure of the solar system from one single point of view—it explains the birth of the planets and other bodies of the solar system out of a cloud of dust and gas that once surrounded the Sun. The fact that the bigger bodies, the planets, have almost circular orbits, leads us to the conclusion that they were formed by the accumulation of many bodies that formerly rotated around the Sun in different orbits. Their genesis from smaller bodies also explains the noticeable difference between the two groups of planets.

We can find an explanation of this phenomenon in the chemical composition and physical condition of the particles in the protoplanetary cloud and in the subsequent evolutionary process.

A more difficult task is the explanation of whence and by what means this protoplanetary gas-dust cloud came into being. I put forward the hypothesis that its formation is due to the Sun's capture of part of one of the gas-dust clouds that are so numerous in our Galaxy. This capture hypothesis provides an explanation of the extention of the planetary system, in other words, the distribution of the angular momentum of the system between the Sun and the planets.

* * *

Scientific experience tells us that the possibility of solving a problem may depend on the way in which it is formulated, and this, as well as its solution, depends on the scientific method adopted. We should look for the solution of a problem in the facts themselves. A generalization of the facts produces a hypothesis which must be elaborated in every way, as far as possible quantitatively, and should be constantly checked up with observed data.

The most important criterion of truth is the criterion of practice. In our present case this is not possible in its simplest form—we cannot create planets no matter what our theory might be. The criterion, however, holds good in another form—the coincidence of theoretical conclusions and the observed data of astronomical practice.

A theory that claims to be true must explain all the features of a phenomenon by one basic hypothesis. The detailed and quantitative elaboration of the hypothesis transforms it into a theory and the criterion of its truth is practical application in the sense mentioned above.

Naturally it is the *main* features of the solar system that have to be explained. Phenomena that we observe today need not necessarily be directly connected with the process of planet formation; many of them are the result of further stages in evolution.

Our task is to explain the origin of the Earth and other planets in the solar system. Later we shall discuss the question of whether the explanation of the origin of other bodies in the solar system forms part of that task and, if so, to what extent; these bodies are the comets, asteroids and meteoric bodies on the one hand and the Sun itself on the other.

We speak of the origin of the *planetary system* and not merely of the planets as separate bodies. The real, natural object of our research is the system of planets surrounding the Sun, which possesses, as a system, a number of characteristic regularities. The origin of planet-like bodies in general is quite a different problem although the two are often confused.

The origin of the planetary system should explain its basic regularities. What are they? Today there are no differences of opinion as to which features are basic and have to be explained firstly. In 1948 ter Haar arranged them in the following four groups.

Group A. Regularities of the orbits: the planetary orbits are almost circular, lie in one plane and revolution is in one direction, with the Sun rotating in the same direction; the equatorial plane of the Sun is near to the plane of the orbits.

Group B. Regularities in planetary distances. The distribution of the planets is obviously not accidental: there is regularity in their distances that was empirically formulated at the beginning of the last century but until recently had not been explained.

Group C. The division of the planets into two sharply distinct groups: the inner planets, Mercury, Venus, the Earth and Mars, are comparatively small but possess great density, rotate quite slowly around their axes and have a small number of satellites, and the outer planets, Jupiter, Saturn, Uranus and Neptune, are big, have lower density, great speed of rotation and numerous satellites. The recently discovered Pluto does not enter into this as it lies on the fringe of the system and may not conform to the same regularities.

Group D. The distribution of the angular momentum. Although the Sun possesses more than 99 per cent of the total mass of the solar system it accounts for less than 2 per cent of the momentum, the remainder being accounted for by the planets.

These are the four groups of features of the planetary system which present-day scientists unanimously accept as basic and which a theory of planet origin must explain.

Ter Haar analyzed existing theories, especially the newest of them, and found that even the best did not explain more than 1 to $2^1/_2$ of these four groups, not one being capable of explaining even three. As we shall see in later lectures, our theory explains simply and naturally the basic regularities of all four groups. A comparative analysis of former and modern hypotheses shows that all of them were limited to an attempt to explain Groups A, B and C, but could not explain Group D, that is, the peculiar distribution of the angular momentum. The only exception, prior to the theory now under discussion, was T. J. J. See's hypothesis (we shall return to this hypothesis later) which, however, did not explain any of the other features and was obviously fallacious.

The law of the conservation of angular momentum is a basic law of nature that has been tested a thousand times over and is as proven as the law of the conservation of energy or the law of the conservation of mass. Angular momentum is the measure of rotary motion. According to the law of the conservation of momentum the sum total of rotations in a closed system remains constant. The rotation may be redistributed, that is, it may be transferred from one body to another, but the sum neither increases nor decreases.

Kant did not understand this. According to his hypothesis the primeval nebula was at rest and then began to rotate, which is impossible. The solar system could not arise out of a state of rest since that would contradict the law of the conservation of momentum.

In order to overcome this difficulty Laplace postulated that the nebula was rotating, as a whole, from the very beginning. If we accept the separation of "rings," the future planets, from the Sun, as suggested by Laplace, then the Sun, having retained the greater part of the mass, should also have retained the greater part of the momentum, that is, it should rotate much faster than it actually does. As we know, the Sun rotates very slowly, one revolution in 25 to 27 days (different speeds for different parts of the Sun) which is less than 2 per cent of the total angular momentum of the solar system.

It is difficult to believe that such a brilliant mathematician and specialist in celestial mechanics as Laplace did not notice this radical contradiction in his hypothesis. Personally I am inclined to believe that Laplace knew it and for this reason did not elaborate his hypothesis in mathematical form but confined himself to description in the 7th Appendix to his book *Exposition du Système des Mondes*.

Be that as it may, Laplace's complacency led to later scientists ignoring one of the basic laws of nature. Angular momentum, however, is one of the most important characteristics of a system in rotation (about a central body or about its own axis). While one form of energy can be transformed into another (the total quantity being preserved), angular momentum always remains angular momentum, that is, the measure of rotation, and can never be transformed into anything else. This peculiar conservatism of angular momentum makes it a particularly important characteristic of the system.

Our theory makes extensive use of the law of the conservation of angular momentum and its redistribution. In this we found the key to the explanation of Group B, regularities in planetary distance, and were also able to explain the origin and direction of the rotation of the planets about their axes.

We explained the distribution of angular momentum (Group D) by the hypothesis of the capture of primordial material by the Sun. The only attempt to approach the problem of the distribution of angular momentum in another way was made later in a counterhypothesis proposed by V. A. Krat and V. G. Fesenkov who postulated that the Sun originally possessed a great angular momentum which it later lost by the ejection of matter (corpuscular radiation). We shall examine this hypothesis together with our own capture hypothesis in Lecture 3.

* * *

In defining our basic problem, the explanation of the genesis of the planetary system in general and of the Earth in particular, we have to admit its close affinity with a number of other scientific problems, both cosmogonic in the broader sense and others. We must also determine which of these problems are to be included in our work and which are independent but have to be taken into consideration.

The solar system includes not only planets but also smaller bodies—asteroids, comets, meteoric bodies and, of course, the central body, the Sun. It will be remembered that there was a lengthy discussion as to whether or not the comets and meteoric bodies belong to our solar system and it has only recently been agreed that they do. The careful study of the orbits of the comets shows that they all revolve round the Sun in elliptical orbits that are in many cases so elongated as to be almost parabolic. With regard to the meteoric bodies that appear in the form of meteors and meteorites, the discussion continued up to recent times because it seemed that visual observation in most cases produced velocities that corresponded to hyperbolic orbits. It was only in the thirties that visual assessment of velocity was replaced by photographic techniques which showed that in all cases the velocities were elliptical.

The smaller bodies, therefore, also belong to the solar system although they differ from the planets in greater or lesser degree in the character of their motion. For this reason the explanation of their origin comes within the scope of our work. Former cosmogonic hypotheses concluded that each group of bodies (planets, comets and others) was of different origin. But this was a fallacious conclusion. The method of explaining phenomena of the solar system without regard to their interrelations is metaphysical and inconsistent. Our theory postulates a *single* process of evolution for all bodies in the solar system, a process that was uniform in all cases but occurred under different conditions which, therefore, not only produced general similarities but also partial differences. We shall examine this problem in the 2nd Lecture and show that both the similarities and the differences are due to the natural evolution of the system.

The Sun is a different matter. The Sun is a star, one of the 10^{11} stars in our Galaxy. The problem of the origin of the stars is one of the most important in astronomy. Let us examine more closely the connections between planetary and stellar cosmogony and the differences that exist between them.

At first glance it seems simplest to suppose that the Sun and the planets originated simultaneously from the same primordial matter, from a nebula, for example. The greater mass formed the Sun and the remainder went to make up the planets. That is what Kant and Laplace imagined. That is what Kuiper, Urey and Fesenkov imagined when they postulated that the cloud was formed together with the Sun when the latter was formed out of a cosmic gas-dust cloud. If this simultaneous formation were true the Sun would possess a correspondingly great angular momentum, which, as we know, it does not. In the 3rd Lecture we shall show in detail that the idea of the simultaneous (in the Kant-Laplace sense) origin of the Sun and the planets meets with insurmountable difficulties. It is quite possible, even quite probable, that the formation of the planets is not far removed in time from the formation of the Sun itself, although, of course, the processes were different.

The planets were formed in the presence and under the influence of an already existing Sun. According to our theory, the Sun is not a passive observer of the formation of the planets but an active participant, the main cause of the process. The Sun formed the planets with all their specific peculiarities by means of its gravitation, light and heat radiation and light pressure. We do not exclude the possible role of corpuscular radiation but give warning against an overestimation of its importance.

We do not yet know the origin of the stars and we have very little reliable knowledge of the evolution of the Sun. Nevertheless it would be incorrect to put off the solution of problems connected with planetary cosmogony until the origin of the stars has been explained. For very obvious reasons we know more about the planets, especially about the Earth, than we do about the stars. Planetary cosmogony has accumulated a sufficient number of facts to attempt a solution of the problem. It is quite possible that the elaboration of a theory of the origin of the stars and a precise knowledge of their evolution will, in turn, lead to some corrections in planetary cosmogony; but the reverse is also true—in building up a theory of the evolution of the Sun the not unimportant fact of the Sun's possession of a planetary system for several thousand million years must also be taken into consideration. Not every theory of the Sun's evolution is compatible with this fact.

It would also be incorrect to ignore the substantial difference in the process of formation of the stars and their planets. V. G. Fesenkov was expressing a widely held opinion when he said that "the origin of the planets does not, in essence, differ from that of the stars." It is true that all processes involving the accumulation of matter into large bodies have something in common, the role of gravitation, for example; it would, however, be wrong not to see that the formation of the stars involves the condensation of matter already existing as a single mass, while the formation of the planets is due to the accumulation of small bodies that were previously revolving around the Sun, each in its own orbit, and that their orbits were different. The processes are essentially different.

If we were to equate the formation of stars to that of the planets we should be ignoring the specific nature of the planetary system as expressed in the four groups of features cited above and by so doing we should be robbing ourselves of the possibility of understanding and explaining these specifics.

Neglect of the specific features of the planetary system has often led to the planets being confused with multiple stars. In both cases we are dealing with a system of bodies held together by gravitation—this much they have in common. The properties of the two systems, however, are very different. The orbits of the visual binary stars differ from those of the planets, being usually elongated ellipses; the triple and, in general, multiple star systems have orbits in different planes. The circular orbits of the planets constitute a very sharp distinguishing feature which points to an origin different from that of the binary stars.

Great interest has been aroused by the recent discovery of invisible satellites belonging to some of the binary stars, for instance, 61 Cygni. The orbits of these satellites as well as their mass can be determined from the observed oscillations superimposed on the orbital movement of one of the components. Some astronomers consider these invisible satellites to be the connecting link between planetary systems and the binary stars. All the orbits of invisible satellites that have so far been computed, however, have proved to be elongated ellipses so that they much more closely resemble components of binary stars than planets.

No system similar to our solar system has, as yet, been observed, and, indeed, such an observation is impossible with the means at our disposal today. There cannot, however, be any doubt that other systems exist.

We believe it to be essential to stress not only the general connections of cosmic phenomena but also the concrete, specific nature of planetary cosmogony. The progress of science would be impossible without this emphasis on the particular and specific. Some astronomers suggest that it would be better to postpone planetary cosmogony until the general problem of the evolution of matter, in particular, stellar matter, has been solved; those who hold these views eventually come, in spite of themselves, to agnosticism, to disbelief in the ability of modern science to solve the problems of the Earth's genesis.

Knowledge of the whole, naturally, helps in the study of the part, but historically science developed, in the main, in the opposite direction—from the particular to the general. The problem of the origin of man, for example, has been solved but the more general problem of the origin of life on Earth is still in the earliest stages of its study.

The development of the planetary system—a process that was small in both time and space, but of great importance to us—we shall examine against the background of the tremendous picture of the cyclic evolution of cosmic matter. The gigantic evolutionary cycle of matter in general is something for astrophysics to deal with; this branch of science has made great progress and is, today, one of the most rapidly developing branches. Our task is more modest—to find out how it happens that certain stars have satellites—the planets.

We do not study the solar system in isolation but as a part of a much bigger system, the Galaxy. If we reject isolated study and turn to the system's environment in the Galaxy we shall have no further difficulty with the angular momentum, since the Sun could acquire from the Galaxy material possessing sufficient momentum.

From our point of view the planets were formed at a comparatively late stage in the development of matter, when Galaxies already existed. The degree of development of the phenomenon depends on the structure and age of the Galaxy under consideration. It therefore follows that the percentage of stars that have had time to acquire satellites is greater in some Galaxies than in others. The process of planet formation, however, is a general one that takes place in every Galaxy so that the number of planetary systems in the universe is infinite. It is in the nature of matter that, in the course of its evolution, it should give rise to planetary systems and planets on which it is possible for life to originate. The number of such systems in the universe is infinite and their infinite number is in the normal order of things.

* * *

Although planetary cosmogony developed out of astronomy, it is a complex problem that involves many branches of science—all the astronomical disciplines and the sciences that study the Earth. Planetary cosmogony must check up both its starting points and its conclusions with these two groups of sciences. Our problem is connected with astrophysics and other branches of science because it includes a study of the state of matter in a period prior to the formation of the planets; when we deal with the final outcome of planet formation we come into contact with geophysics and geology; the cosmogony of a planetary system should start from the state of matter in the protoplanetary period as shown by astrophysics and should lead up to a present state of the planets, especially the Earth, which accords with the data gathered by the geophysicists and geologists.

If the problem is to be approached in this way it falls naturally into three parts: we have to

a) discover whence and in the course of what process there appeared in the neighbourhood of the Sun the material from which planets were later formed;

b) define the state of that material before the planets were formed and from that definition and the laws of nature determine the chief properties of the planetary system, i.e., explain cause and effect.

c) deduce from these properties and processes geophysical, geochemical and geological results.

The three components, *a*, *b* and *c*, differ in time: the first belongs to the period before the planets were formed, the second to the process of planet formation and the third to the later evolution of the planets, the Earth in particular, subsequent to their formation.

Of these three problems, the second is the more specific as far as planetary cosmogony is concerned, it may be called, in fact, *the central problem of planetary cosmogony.* We shall begin to sketch our theory from this central problem. As we shall see, the careful study of the present condition of the planetary system gives us a direct and definite answer to the question: in what state did the material exist prior to the formation of the planets? From this state we obtain, as effects, the explanation of all the chief properties of the system listed in points A-D above. In this sphere we are so well provided with facts that the element of the hypothetical is reduced to a minimum that is gradually disappearing in the course of scientific work that is producing a more or less complete theory. It will be described in Lecture 2.

The central problem, therefore, can be taken up and solved to a certain extent independently of the first (*a*). This relative independence is very important because the farther back in time our investigations take us, the fewer the facts we have to go on, the less certain are our judgements, the more hypothetical they become. Such is the case with part *a*.

Once we have elaborated a theory of the formation of the planetary system we have ample means at our disposal to attack part *a*, which we shall do in Lecture 3. Lastly, in Lecture 4 we shall deal with certain conclusions that are to be drawn from the application of the theory to the evolution of the Earth and its present state.

* * *

The first thing, then, is to determine the state in which the protoplanetary material existed before the planets were formed and to do so on the basis of facts drawn from the planetary system.

One of the best known features of the planetary orbits—that they are almost circular—is the key that opens up the preceding state of the material of which the planets are made.

The planets move along almost circular orbits. Other members of our solar system, the asteroids and comets, have, in the majority of cases, orbits that are noticeably elliptical, many of them very greatly eccentric. In general, we know from the basic laws of celestial mechanics, the laws of Newton and Kepler, that the orbit of one body moving about another under the influence of its gravitation should be a conic section—ellipse, parabola or hyperbola—but the laws do not require that the orbits be ellipses with very little eccentricity, that is, almost circular. Naturally, circles are to be found amongst the ellipses, the result of accidentally favourable initial conditions, but why should *all nine planets* move along almost exactly circular orbits? This cannot be the result of the coincidence of nine accidents and must have a common cause.

This was a problem upon which Newton speculated. At the end of his famous book he said that the circular orbits of the planets could not be the result of mechanical laws alone. But Newton was unable to find any better explanation than to attribute it to an act of the deity.

Newton did not pose the problem of scientific cosmogony, that is, the origin of bodies as the result of the evolution of matter. This was not only because of Newton's religious beliefs but also because of his metaphysical mode of thought: the heavenly bodies were for him something given and unchanging once and for all time. Our task, on the contrary, is to disclose the origin of the planets with all their properties, including that of the circular orbits, as a process of the evolution of matter.

Despite Newton's warning, later investigators frequently ignored the fact that *circular complanar* orbits constitute a specific feature of the planetary system. It was because they forgot this that they could compare planetary systems with binary or multiple stars, exaggerating the analogy between these formations, and try to find a common origin for them. We have already spoken of this fallacy.

Thus we get to the point: celestial mechanics do not require circular orbits but the orbits of the planets are close to circular. From what cosmogonic process did this phenomenon result? If we do not want to invent special, complicated and improbable phenomena, there is only the one simple and natural process left—the planets were formed by the agglomeration of a large number of bodies each moving around the Sun in its own independent, elliptical orbit. The original independent orbits may have possessed all sorts of eccentricities, they could have been ellipses elongated to any extent and in any direction. When large numbers of bodies were joined into a single planet their orbits were naturally, averaged, and, as a result, they could only be fully symmetrical, i.e., circular, and close to a plane perpendicular to the vector of the principal angular momentum of the whole system.

Have any other explanations of the circular nature of the orbits been offered? They have. Some authors favour the concept of the so-called resisting medium.

It was supposed that even if the planets had originally possessed elongated elliptical orbits they could gradually become circular if there were a "resisting medium" of dispersed matter around the Sun. This idea, used in a number of cosmogonic hypotheses, was propounded by See at the beginning of the present century. The See hypothesis says that the planets were originally independent bodies alien to the solar system and that they were captured by the Sun one by one. If, however, the planets were captured one by one they would move in various directions, in different planes and their orbits could be elongated to any extent. In order to get out of this difficulty See assumed that there once existed an extensive and rather dense medium in the vicinity of the Sun that offered resistance to the movements of the planets. This resistance resulted in a reduction of the velocity and in the hyperbolic orbits becoming elliptic (this constituted the capture). According to See that same resistance reduced the eccentricity of the orbits to its present degree.

There are, of course, differential equations that show the effect of resistance on the elements of an orbit. They show that eccentricity slowly—very slowly—decreases. These works, however, used a scheme that is far removed from reality: it assumed that a planet moves through the medium in the same way as a ship moves through water, i.e., against resistance but with no change in mass. The interaction of planet and medium, however, is of an entirely different character. The particles that constitute the medium do not flow round the planet but strike against it (or enter its atmosphere) and, in the majority of cases, *adhere* to it. From this it follows that the "resisting medium" is, in reality, a *feeding* medium.

The action of the resisting medium with the change in mass taken into consideration has been mathematically studied by Nölke. It turned out that for the planet to reduce the eccentricity of its orbit from, say, 0.5 to 0.1, it had to adsorb five times its own mass from the medium! Obviously there could be no question of the action of an independent medium on a passing planet; in actual fact the process is one of the *formation of the planet out of the medium* around a small nucleus, i.e., the matter from which the planets were formed was previously in a dispersed state. The mathematical solution of the problem is not to be found by the use of equations showing disturbances due to resistance, but by the method of averaging the energy and angular momenta of the particles from which the planets are made up. The resisting medium, in actual fact a feeder, has led us by a roundabout way to the same dispersed protoplanetary matter.

Jeans also made use of the resisting medium. According to his hypothesis a mass of gaseous matter was torn off the Sun by the gravitation of a passing star. It had the shape of a cigar with one end pointing towards the passing star. This cigar then broke into a number of parts, the planets. Jeans was fully aware of the fact that the planetary orbits, obtained in such a way, would be greatly elongated ellipses. This elongation was even necessary for him to tear the satellites from the planets by means of the tidal influence of the Sun at the moment of the perihelion passage of the condensation.

How, then, were the planets to be forced into their circular orbits? Jeans again made use of the same resisting medium; he assumed that part of the matter torn off from the Sun was dispersed to form a gaseous medium around it whose action resulted in the circular orbits as in See's hypothesis. Jeans in his hypothesis ignored the fact mentioned above—for a substantial change in the eccentricity of the orbits almost the entire mass of the planets would have to be formed from that dispersed medium and could not have been produced from a piece of the "cigar."

Other attempts have been made to explain the circular orbits. V. G. Fesenkov in 1944-1945 proposed a new variant of the planet formation hypothesis which he called the "rotational hypothesis," according to which the Sun formerly rotated with greater velocity than at present, so fast, in fact, that rotational instability set in. Fesenkov's idea was that this led to the formation on the Sun of a bulge several solar radii in size. In the end this bulge separated and broke into a number of pieces, the planets. Since the bulge rotated together with the Sun as a single whole until its partition, all of its parts moved in circular orbits. This explained the circular form of the orbits.

The "rotational hypothesis," especially the assumption of the bulge, led to very great difficulties and contradictions, some of which were noted by the author himself. The attempt to justify the bulge was more hopeless than the attempt to justify Jeans' cigar. There is no need to analyze the "rotational" theory in detail as its author's views have since changed. In recent years Fesenkov has come to regard one of the variants of the cloud of dispersed matter as being the state of the medium before the formation of the planets.

Thus the character of the planet orbits tells us that the planets were formed from dispersed material.

An analysis of another specific feature of our planetary system—the division of the planets by composition and mass into two groups—showed the great importance of the degree of evaporation (or, on the contrary, freezing) of ice particles at different distances from the Sun. The results of this analysis made it clear that the primitive state of planetary matter could only have been that of a gas-dust cloud and not a simple dust (meteorite) cloud as was thought possible during the early years of the development of the theory.

Solid particles of stony or icy composition present in the cloud constituted the raw material of the majority of the bodies in the solar system. An examination of the evolution of this cloud gives us the explanation of all the other fundamental regularities occurring in the planetary system. It is important to mention that we shall not need any other supplementary hypotheses to explain these regularities. They are the simple, natural and logical outcome of the formation of the solar system by the evolution of a rotating gas-dust cloud that at one time surrounded the Sun. The study of the evolution of this cloud brings us closer to an understanding of the causes and conditions under which the dust and gas cloud itself came into being in the vicinity of the Sun.

Lecture 2.

FUNDAMENTAL REGULARITIES OF THE PLANETARY SYSTEM—THE RESULT OF GAS-DUST CLOUD EVOLUTION

The development of planet cosmogony in general has resulted in the conviction that the material of which the. planets are composed was, in its preceding stage, in a dispersed state. This is a general feature, to a greater or lesser degree, both of the classic hypotheses of Kant and Laplace and of the majority of the modern theories.

The fact that a gas-dust cloud is in all cases a prerequisite does not presuppose that cosmogonic theories are the same throughout. Modern conceptions differ with regard to the evolution of the cloud and also with regard to its origin.

There are differences of opinion at every step, mainly on the question of how, at what rate and under the influence of what forces the particles were aggregated into bigger bodies. Our theory says that the planets were formed by the gradual collection of solid matter from the surrounding medium by originally small embryos. Kuiper and others consider the condensation of large pieces of the cloud under the influence of their own gravitation to have been of primary importance. They believe that the initial mass of these protoplanets was enormous, a hundred or even a thousand times that of the present planets. A big difficulty, however, arises: what has happened to the excess mass? Why, for example, is the Earth now so small? The champions of this type of cosmogonic theory hold that the surplus matter gradually evaporated from the protoplanets and was scattered in space. I.S. Shklovsky showed that such a dissipation process takes place very slowly and that it would have taken much longer to get rid of the surplus than the 5,000-6,000 million years that have elapsed since the formation of the planets began. Apart from that, if the Earth had begun as a massive planet and later lost most of its mass, then its rotation would inevitably have ceased because particles escaping from the surface possess the greatest angular momentum per unit of mass. As the Earth, however, rotates it cannot have lost the greater part of its original mass.

Can we study the evolution of the cloud without first establishing its origin or accepting any definite hypothesis in that field? It seems that we can. In all the parts of the universe that we can study the stars and interstellar matter have approximately the same atomic composition, with slight individual deviations. There are greater differences in the physicochemical state of the clouds: the ratio of the solid and gas phases, the presence of electric charges (ionization). Observation shows that these differences are mainly due to star neighbours (or absence of neighbours) and to the temperature of the latter. We have in mind here a cloud in the immediate neighbourhood of the Sun, whose gravitation and radiation determine the further evolution of the cloud.

There is no reason to suppose that the circumsolar cloud of protoplanetary material, of whatever origin it may have been, differed substantially in composition from the galactic nebulae. In addition to the gases (mainly hydrogen) it contained solid particles (mainly, but not solely, in the form of dust) a considerable part of which consists of H_2O, CH_4, CO_2, NH_3, CN and other light compounds in the form of ice particles. In addition to the ice particles there were also silicates and metals.

What course did the evolution of this circumsolar cloud take? Was it certain to lead to the formation of planets? How were the planets really formed?

An investigation of the various factors of the evolution of the gas-dust cloud shows that collisions between particles equalized their velocities until they were close to a velocity that corresponded to a circular orbit situated near a central plane determined by the total angular momentum of the cloud. The result of this was that the dust component of the cloud had to flatten and condense, collisions became more frequent and the free path diminished. The irretrievable loss of mechanical energy in inelastic impacts, the angular momentum being retained, led to a further flattening of the system and the accumulation of the particles in a disc of higher density—the first stage towards the collection of dispersed matter into planets.

The question naturally arises: how did the process of growth begin, what was the "condensation nucleus" or "embryo" of the planets? If there were bigger bodies present in the circumsolar cloud, as I postulated at the very beginning, they could easily have become the embryos of the future planets. The orbits of the small particles and those of the bigger bodies often crossed and the collisions led to the cohesion of some and the splintering of the others. If they met at high velocities they, of course, broke up, with the resultant loss of energy. Even if splintering predominated at first it helped to reduce the kinetic energy of the relative motion, i.e., to equalize the velocities. Further collisions became more frequent but with lower relative velocities, so that less splintering occurred. A non-mechanical factor, the transformation of a considerable part of the kinetic energy into heat energy, determined and completed the evolution.

Did larger bodies exist in the protoplanetary cloud from the very beginning? The observation of light absorption, it has been theoretically demonstrated, reveals only dust particles 3×10^{-5} cm. in diameter. There is, however, nothing against the assumption that larger bodies also exist, due to atoms and molecules of gas freezing on to the dust particles. Although the existence of these larger bodies is quite possible we have no actual proof of their presence. This has given rise to some doubt as to whether or not a gas-dust circumsolar cloud led to the formation of planets, but L.E. Gurevich and A.I. Lebedinsky removed these doubts by proving that even if the primordial embryos did not exist, even if the cloud had consisted exclusively of gas and dust, the condensation must have taken place.

Using the methods of statistical physics they analyzed the inevitable evolutionary process in a system of solid particles with great angular momentum and sufficient total mass, a process governed by the gradual loss of energy due to collisions between the particles. They showed that the following must occur:

a) the relative velocities of the particles are reduced by collisions; this results in the flattening of the system with a consequent increase of density leading to a still greater frequency of collisions;

b) when a certain critical density is reached the system cannot remain in its former state; under the influence of gravitation the intensive formation of condensations begins;

c) these condensations are flattened in shape and have a mass comparable to that of the asteroids;

d) the condensations in turn are bound to collide (owing to their small free path) and agglomerate into a small number of big bodies, the planets.

In a short lecture I cannot give the proofs of these statements. The authors have given proofs that represent not only the qualitative side of the processes but also a number of quantitative relationships for every stage of evolution.

In order to simplify their proofs the authors made a detailed study of the case of a uniform dust cloud although, in principle, the method is equally suitable for cases of clouds that also contain larger solid particles and gas. We must here mention that Edgeworth, in England (1949) also investigated the role, in the evolution of the cloud and the formation of planets, of the loss of energy through collision: Edgeworth examined the problem from a standpoint close to ours but his arguments were not free of error and arbitrary assumptions and were not sufficiently convincing.

The study of the evolution of the gas-dust cloud shows that its dust component had to become flatter and denser until it formed a disc of higher density.

An important stage in the evolution of the cloud was the formation of a large number of intermediate bodies of asteroid size. There are two ways in which this could have occurred. Firstly as shown by Gurevich and Lebedinsky, the dust component could have been flattened to such an extent that the density of the material became sufficient for the formation of numerous small, primary condensations capable of withstanding the tidal influence of the Sun. Some of these, condensed into small bodies, might be the embryos of the future planets. Secondly, Safronov has computed that where the density of the dust disc is approaching the critical value, the larger particles grew so rapidly by the accumulation of dust matter from the surrounding medium, that bodies as massive as the primary condensations could have grown up in a short time. Gravitational instability, to which there is undoubtedly a tendency, might, therefore, not have time to produce any effect before the planet embryos were formed by other means.

Is it really possible for the dust disc to flatten sufficiently for its density to reach the critical value needed for gravitational instability to supervene? Irregularities in the process of contraction, the presence of bigger and growing particles in the cloud are sufficient to hinder the extreme flattening process that is essential for gravitational instability to operate.

It is still difficult to draw a detailed picture of the early stages of the evolution of planet embryos. Their collision led to their cohesion or to their splitting after which the fragments could again be drawn into the process of accumulation. In general, the predominating process was one of the conglomeration of matter. The fragments, together with "primary" particles, constituted the dispersed matter out of which the embryos grew, at first rapidly and then more and more slowly as they swept up the surrounding matter. When some of the embryos had acquired the size of big asteroids, the chaotic movement of the particles again increased under their dynamic influence. As the bigger bodies grew, however, they ceased to fear collisions since the splintered material, in the majority of cases, remained within their field of gravity and fell back on them. The highest rate of growth belongs to those embryos whose effective radius is much greater than their geometric radius, especially those placed at regular distances from the Sun so that they least of all interfere with each other in acquiring matter from the medium. From these a small number of massive bodies, the planets, is gradually formed.

* * *

The circular orbits result from the natural statistical averaging of the motions of the separate bodies that agglomerate to form the planets. This natural averaging provides a simple explanation for the next two basic regularities—the motion of all the planets in practically the same plane and in the same direction. Both these result from the averaging of the *angular momenta of many bodies.*

As we have already said, former hypotheses did not pay sufficient attention to the law of the conservation of angular momentum. For an analysis of the evolution of a complicated system, however—for example, a cloud of particles in a state of transition into asteroidal bodies and later into planets—the conservation of momentum, that is, the conservation of the total rotary motion, in the system, is the key to understanding the phenomena and foreseeing the results of evolution.

Angular momentum is, as we know, a vector directed along the axis of rotation (the direction is regarded as positive if the rotation, as seen from the end of the vector, is anticlockwise), and is equal to the product of the mass, the linear velocity (in relation to its axis) and the perpendicular distance from the axis.

Every particle, every body in the system had its own angular momentum in respect of the Sun, but the momenta differed in quantity and direction. When one body passed close to another, gravitational disturbances changed their orbits and the bodies exchanged part of their momenta and energy. In cases of collision part of the mechanical energy was transformed into other forms of energy. But in all cases the sum of the momentum vectors (added geometrically, i.e., by the parallelogram rule) remains unchanged. The sum total of the momenta, the principal momentum of the system, remains unchanged in quantity and direction throughout the entire evolution of the system. The plane that passes through the Sun perpendicular to the vector of the principal momentum is usually called the constant or Laplace plane of the system.

A system of bodies whose total momentum is zero could not have given rise to a planetary system like ours. In the general case the momentum is more than zero and may even be very great. If a large number of bodies with big momenta join together—it does not matter how—into one big body, then the latter will revolve about the Sun with the total angular momentum possessed by all the bodies before their union (a very small portion of the momentum may be transferred from orbital to rotational momentum about the body's own axis).

A swarm of comparatively large bodies and small particles existed for a rather long time before their collection into planets. During all this time the bodies and particles mixed and acted on each other. The amount of momentum was different in different parts of the swarm, but the directions of the total momenta of those bigger parts of it that went to form the planets could not have been greatly different. For this reason the momenta of the planets must have been approximately parallel. This explains why the planets move in approximately the same plane: all of them have orbits close to the constant (Laplace) plane and move in one and the same direction.

We see, therefore, that all the regularities of the planetary orbits—motion in approximately the same plane, in the same direction and almost in circles—can be explained in a simple and natural way by the idea that the planets were formed by the agglomeration of a large number of bodies.

* * *

We shall now examine the other and more subtle features of our planetary system, and will begin with the law of planetary distances.

Is there any regularity in the distances of the planets from the Sun and how is it to be explained? This is a question that has long interested astronomers. Take, for example, the Bode law, published in 1772. If we take the distance from the Earth to the Sun as unity and the distance from Mercury to the Sun as being approximately 0.4, then the distance from the Sun to the other planets is expressed by the following formula, according to the Bode law:

$$0.4 + 0.3 \times 2^n,$$

where n is the number of the planet (for Venus $n = 0$, for the Earth $n = 1$, etc.).

Let us compare the figures given by the Bode law with the actual measured distances.

Table 1

	Mercury	Venus	Earth	Mars		Jupiter	Saturn	Uranus	Neptune	Pluto
Bode law	0.4	0.7	1	1.6	2.8	5.2	10.0	19.6	38.8	77.2
Actual distance	0.39	0.72	1	1.52	—	5.2	9.54	19.19	30.07	39.5

In many cases there is an astonishing coincidence of figures, but there are also big discrepancies. The planet that, according to the law, should come between Mars and Jupiter does not exist and the space is but poorly filled in with asteroids whose total mass is less than that of any of the planets. The figure for Neptune is unsatisfactory: if it is applied to Pluto to attain greater coincidence, then it becomes quite incomprehensible why the latter should be considered a regular member of a series when the much bigger and more massive Neptune is left out.

The Bode law has been discussed for almost two centuries. Some scientists have believed it to be a real natural law that has not yet been explained while the others, probably the majority, regarded it only as the accidental coincidence of two series of figures.

Our theory approaches the problem of the planetary distances in the same way as it does other features of the motion of planets, that is, we consider, in mathematical form, that process of natural averaging that takes place during the formation of planets. We shall take as our basis the angular momentum and shall, in future, speak of the angular momentum per unit of mass (specific angular momentum).

Let us examine the development of two neighbouring planet embryos that are in a state of growth. If their orbits are very close they soon sweep up bodies and particles moving in the space between them. If the two planet embryos do not adhere to form one body they will continue to acquire mass and angular momentum mainly from bodies moving on the outer side of the exhausted zone. Therefore the angular momentum per unit of mass will be reduced in one planet and increased in the other and the radii of their orbits will begin to differ. The very process of the growth of the planets by the collection of bodies and particles includes the principle of the regulation of distances between them.

Let us look for the law of planetary distances without bothering about the detailed kinetics of the process. Particles in the cloud have specific angular momenta of different values. Let the whole mass of those particles of the cloud that go into the planets be distributed by the value of the specific angular momentum q in accordance with some differential law of distribution $f(q)dq$. We shall show that every law of distribution, i.e., every function $f(q)$, has its corresponding law of planetary distance. We suppose that when planets are being formed those particles have the greatest chance of joining the planet whose specific angular momentum is least different from the planet's. Some particles, of course, may join a planet other than their "own," but such deviations are mutually compensated so that for purposes of computation it may be assumed that the particles are all distributed along the sections of the axis of specific angular momentum allotted to each planet. The boundary between sections will be a specific angular momentum equidistant from the specific angular momenta of two neighbouring planets. Let β_n be the value of the angular momentum corresponding to the boundary between the sections allotted to planets n and $n+1$, the specific angular momenta of which will be q_n and q_{n+1} respectively. Applying what has been said above we get:

$$\beta_n = \frac{q_n + q_{n+1}}{2} \tag{1}$$

When the particles of a section unite to form a planet their angular momenta are averaged so that the specific momentum of the planet will be:

$$q_n = \frac{\int q f(q)\, dq}{\int f(q)\, dq} \tag{2}$$

in which the integration limits are β_{n-1} and β_n.

Substituting q_{n-1}, q_n and q_{n+1} for these β in accordance with equation (1), from equation (2) we get a difference equation for the momenta q_n. The q_n of the planets, in view of their circular orbits, is $k \sqrt{M} \sqrt{R_n}$, where R_n is the orbital radius of the nth planet, M, the mass of the Sun, and k, the gravitational constant. Formula (2), therefore, gives us the *law of planetary distances* corresponding to the distribution function $f(q)$. The physical significance of this formula is that at the time of the formation of the planets specific angular momenta were averaged, the weight function of this averaging being $f(q)$, which characterizes the distribution of mass against specific angular momentum.

For each concrete $f(q)$ there is a concrete law of distances. If we assume, as we usually do in physics, that a function of the cq^{λ} type is a sufficiently precise approximation of $f(q)$, then, by integration, we get:

$$q_n = \frac{\lambda + 1}{2(\lambda + 2)} \frac{(q_{n+1} + q_n)^{\lambda + 2} - (q_n + q_{n-1})^{\lambda + 2}}{(q_{n+1} + q_n)^{\lambda + 1} - (q_n + q_{n-1})^{\lambda + 1}} \quad (3)$$

Equation (2), or its special form (3), interconnects the distances of three neighbouring planets from the Sun for every $f(q)$, because the values q_{n-1}, q_n and q_{n+1} are proportional to $\sqrt{R_{n-1}}$, $\sqrt{R_n}$ and $\sqrt{R_{n+1}}$. Our law, therefore, is expressed in the form of a difference equation of the second degree. The extent to which the theoretical relation coincides with the real one can be checked by means of the equation, without solving it. If we substitute the values of $\sqrt{R_n}$ for three neighbouring planets of one group in equation (2), (take, for example, Jupiter, Saturn and Uranus) we see clearly that with very different values of λ we get quite satisfactory results: the right member of the equation differs from the left only by a small percentage, by no more than could be expected from a statistical law that does not account for inevitable fluctuations in the density of the cloud. Such a comparison of the planets in threes, therefore, does not enable us to give one single value for the mass distribution function $f(q)$. This is not to be wondered at since we know that different methods of reaching an average, for example, the arithmetical or the geometrical average, etc., are not widely different in their final results. It is important to note that law (2) is a very general law which holds good for a very extensive class of functions of the distribution of mass against specific angular momentum.

If, however, we make the natural assumption that the mass distribution $f(q)$ has no sudden jumps or breaks and is to be expressed by the same simple function for whole groups of planets as for threes (taking two separate groups for the 4 nearer planets and the 5 distant ones), then the corresponding difference equation must be solved in order to compare our computed figures with the real ones. Two arbitrary constants will be used and they can be determined from the observed distances, for example, of the first and last planets of each group.

The simplest case is that of $\lambda = 0$, i.e., when $f(q)$ is a constant. Then the difference equation (3) becomes:

$q_n = \frac{q_{n+1} + q_{n-1}}{2}$, the general solution of which is:

$q_n = A + Bn$, where A and B are arbitrary constants. Substituting distances for angular momenta we may express the law as follows:

$$\sqrt{R_n} = a + bn, \tag{4}$$

i.e., "the square roots of the distances of planets from the Sun are in arithmetical progression." This is the simplest form of the law of planetary distances.

If we determine the values of a and b separately for each of the two groups of planets as outlined above, we get the following table in terms of the astronomical unit, i.e., the mean distance from the Earth to the Sun.

For the outer group of planets:

Table 2

Planets	Jupiter	Saturn	Uranus	Neptune	Pluto
$\sqrt{R}$ theoretical	2.28	3.38	4.28	5.23	6.28
$\sqrt{R}$ actual	2.28	3.09	4.38	5.48	6.29

and for the inner group of planets:

Planets	Mercury	Venus	Earth	Mars
$\sqrt{R}$ theoretical	0.62	0.82	1.02	1.22
$\sqrt{R}$ actual	0.62	0.85	1.00	1.23

The coincidence is very good for a statistic law and is much better than that of Bode's law. In particular our law differs from Bode's law because Neptune and Pluto fit in so that their presence could have been forecast if the law had been known before.

It is interesting to note that the satellites of the major planets fit into a similar law: this law has been found empirically by S. Petrov. By means of trials he arrived at the square law of distances for the satellites of the planets using different constants for each of the planets, but the law is very near to ours in type.

While formula (4) quite satisfactorily gives the real distances of the planets from the Sun, the law $f(q) =$ const. is not in accord with the actual masses of the planets. If I wanted to look for formal mathematical explanations, the formulae (2) and (3) give plenty of scope for it. With $\lambda = -3$, for example, the difference equation (3) is reduced to a simple form:

$$R_n = \sqrt{R_{n-1} \times R_{n+1}},$$

with the general solution $R_n = AB^n$. In this case there is a satisfactory agreement both for the distances and for the mass of the giant planets. It must, however, be remembered that $f(q)$ changed during the evolution of the cloud, primarily because of the change in temperature conditions. This problem has still not been solved. But the law of planetary distances and the law of the distribution of planet mass must depend not only on the primordial distribution of mass, but also on the various transformations of matter in the course of the cloud's evolution. It is, therefore, essential to continue seeking a theoretical foundation for the law of planet mass; it will no doubt prove to be closely connected with the law of planetary distances.

Kuiper and Fesenkov have recently attempted to evolve a law of planetary distances. Kuiper reasons as follows: he first of all convinced himself that gravitation between neighbouring planets could not have determined the law of planetary distances since it is hundreds and thousands of times less than the Sun's gravitation. After this Kuiper deduced a law of planetary distances using the concept of tidal stability. He assumes that the condensing protoplanetary cloud, when it reaches "Roche's critical density," breaks up into a number of big condensations, the protoplanets. When the density is greater than the "critical," the force of gravity acting inside the condensation is so great that it cannot break up owing to the difference in the Sun's pull on its nearer and more distant parts. Here Kuiper makes a quite artificial assumption that only one protoplanet is formed for each planet. Examining two neighbouring planets that have just been formed and taking the distance between their orbits as Δ, and, for the sake of convenience, regarding them as equal and spherical, Kuiper assumes that their radii are equal to $\Delta/2$. To express "Roche's critical density" he takes the mass of the Sun, M, the average distance of the protoplanet from the Sun a, and the mass of the protoplanet m, and gets the formula:

$$\frac{m}{M} = 2\left(\frac{\Delta}{a}\right)^3. \qquad (5)$$

If we take m as the mass of the given planet, and Δ the distance between it and the next, then formula (5) does not agree with the actual distance. Greater coincidence is obtained if the right member of the equation is divided by 1,000. Kuiper, therefore, introduces the assumption that the original mass of the protoplanet was some hundred times greater than its present mass, that is, over 99 per cent of the mass evaporated after the protoplanet had become a separate entity in the process of its transformation into a planet. Even after this arbitrary change of mass by a hundred or a thousand times only a very rough approximation is obtained. Tidal stability really is of importance to planet cosmogony but its significance is not in its direct connection with the law of planetary distances.

Fesenkov, like Kuiper, makes use of the concept of tidal stability to deduce a law of planetary distances. To get a law that approximates reality, Fesenkov makes the arbitrary hypothesis that tidal influence on the part of a neighbouring planet comprises some small part K of the tidal influence of the Sun, and that K is the same for all planets. This, however, is not enough: the masses of the planets of the Earth group had to be increased 30 times over which was tantamount to accepting different values of K for the two groups of planets. Furthermore, in order to represent the distances of all planets simultaneously, the mass curve is smoothed out, with Jupiter given a mass only half its real figure and with an asteroid planet added.

Let us look at the physical side of Fesenkov's method. There can be no doubt that the tidal force of the Sun is considerably greater than that of a neighbouring planet. This means that if the protoplanet is not stable as far as the Sun's tidal action is concerned, its stability to the influence of other planets is of no importance: it would break up. If the formation is stable to the Sun's influence the effect of the neighbouring planets can be disregarded. Thus, the whole deduction is devoid of a basis in physics. He begins by introducing fantastic, unfounded suppositions and then applies perfectly good mathematical machinery.

* * *

Now let us look into the cause of the axial rotation of the planets and the formation of satellites. As we shall see, these two processes are closely connected. The rotation of the planets has not been explained by any of the previous cosmogonic hypotheses. We shall be able to explain it because in our theory the conversion of energy during planetary formation is taken into account.

It is well known that all planets not only revolve around the Sun but also rotate about their own axes. All the planets except Uranus rotate in the direction of their orbital motion ("direct" rotation). The majority of the planets have satellites, from one to twelve in number, and most of them revolve around their planets in the same "direct" manner although there are also some "retrograde" satellites.

The axial rotation of the planets, of course, differs from their orbital rotation around the Sun. But in both cases there is rotation which enters into the same constant—the total angular momentum of the solar system. The amount of axial rotation, its momentum, was taken, therefore, from the original momentum of the gas-dust cloud. How and why did this happen? To approach the question of planet rotation correctly we must begin from the fact that the diurnal rotation possesses energy and angular momentum and must be examined together with the total balance of energy and momentum and their redistribution during the process of planet formation.

When particles accumulate to form a planet both their energy and their angular momenta should be conserved: the loss of kinetic energy transformed into heat energy by the collisions must be taken into consideration. There is an averaging of the specific energy and the angular momentum of all particles during the formation of the planet. As the averaging of the momentum follows a different law from that of the energy it is practically impossible for a planet to acquire an orbit on which orbital motion would absorb all the energy (less losses from collisions and heat) and all the angular momentum. *A surplus or deficiency in the total momentum* of the particles forming the planet, as compared with the orbital momentum of the planet, *leads to its rotation* in one direction or the other. Such is the basic idea we shall now develop in greater detail.

We have seen that during the evolution of the cloud its dust component has flattened and the orbits of the particles have approached the circular. Then intermediate bodies of asteroidal size are formed from the particles and these bodies disturb one another so that they begin to move in elliptical orbits. The accumulation of such bodies and particles in separate regions of the cloud (swarm) leads to the formation of planets.

As bodies and particles approach a planet their potential energy is reduced and their kinetic energy is consequently increased by the same amount (the velocity of the bodies increases). From the moment the bodies adhere to a planet their potential energy is preserved for all time, but where does the kinetic energy go? There are three manifestations of this energy. Firstly, the orbit of the planet and its orbital energy may change after the adherence of other bodies; secondly, the rotational energy of the planet may change and, thirdly, part of the kinetic energy changes to heat when collisions occur. All these changes of energy must be accounted for in our balance.

Let us compare two states of the system—the initial (the multitude of particles from which the planet was formed) and the final (the planet). For the time being we shall ignore the satellites.

Particles	*Planet*
Orbital kinetic energy of the particles.	Orbital kinetic energy of the planet.
Potential energy of the particles in the Sun's gravitational field.	Rotational energy of the planet.
Mutual potential energy of the particles.	Potential energy of the planet in the Sun's gravitational field.
	Potential energy of the planet as a sphere.
	Kinetic energy transformed into heat during collisions.

The sum of all forms of energy in the left-hand column should be equal to the sum of the right (it goes without saying that potential and kinetic energy must be taken with the proper mathematic sign).

In the same way the sum of all the angular momenta of the particles should be equal to the orbital angular momentum of the planet plus its rotational momentum.

For simplicity we shall take a case in which the orbits of all particles in the region are circular and lie in the same plane (corrections for ellipticity and inclination of orbits can easily be made). Let ρ be the radius of the orbit of a particle and let $\varphi(\rho)\,d\rho$ be the distribution function of the mass of the particles, then, applying known formulas, the mass of all particles in the region (i.e., the mass of the planet) is:

$$dm = \varphi(\rho)\,d\rho, \quad m = \int_{R_1}^{R_2} \varphi(\rho)\,d\rho,$$

where R_1 and R_2 are the boundary radii of an angular region. The sum of the potential energy of the particles in the Sun's gravitational field and their kinetic energy is equal to:

$$\frac{k^2M}{2}\int_{R_1}^{R_2}\frac{\varphi(\rho)\,d\rho}{\rho}$$

where M = the mass of the Sun; their momentum is:

$$k\sqrt{M}\int\sqrt{\rho\varphi(\rho)\,d\rho.}$$

For the formed planet with a mass m and an orbital radius R the energy in the Sun's gravitational field and the orbital angular momentum are:

$$\frac{k^2Mm}{2R} \text{ and } km\sqrt{M}\sqrt{R} \text{ respectively.}$$

By substituting these expressions in our balance we get the equations:

$$\frac{k^2M}{2}\int_{R_1}^{R_2}\frac{\varphi(\rho)\,d\rho}{\rho}-\frac{k^2Mm}{2R}=$$ (the potential energy of the planet as a sphere) — (the mutual potential energy of the particles) — (kinetic energy of rotation) — (loss of energy), (6)

$$k\sqrt{M}\int_{R_1}^{R_2}\sqrt{\rho\varphi}(\rho)\,d\rho-km\sqrt{M}\sqrt{R}=$$ (rotational momentum of the planet). (7)

Let us consider the loss of kinetic energy during planet formation. After the first stage of the cloud's evolution—the flattening of the dust component and the approach of the orbits of the particles to the circular—collisions do not stop. During the formation of intermediate bodies of asteroidal size the individual particles will continue to collide, losing part of their kinetic energy in heat; after the formation of the planet embryos heat will again be generated when asteroidal bodies or particles fall on them. We cannot determine these losses quantitatively but there can be no doubt they are very great. The sign in the right member of equation (6) depends on the extent of the losses: if they are big enough the sign will be negative and if they are small it will be positive. As losses during the formation of a planet are considerable, the right member of equation (6) is negative.

It can be proved mathematically* that when (6) has a negative right member, the right member of (7) will *always be positive* for any distribution function $\varphi(\rho)$. This means that the rotational momentum has the same sign as the orbital momentum of the planet, i.e., *the rotation of planets must be direct.*

From our theory it follows that the rotational momentum of the planet is a small quantity, the difference between two great quantities, each of which is some statistic mean. In spite of the general tendency to direct rotation there is also the possibility of retrograde rotation in some cases. With differences in the distribution of orbital inclination it is inevitable that the resultant momentum of the planets will not always be exactly parallel to the main momentum of the system. Deviation from the parallel leads to certain differences in the orientation of the planet orbits and in the lateral components of the rotational momentum, which, owing to the smallness of the angular momentum of axial rotation itself, leads to the rotation axes deviating rather considerably from the parallel: this may go as far as it has done with Uranus. Such phenomena actually exist and, far from contradicting our theory, are foreseen by it. It is worthy of note that in Jupiter, the planet that came into being by the agglomeration of the greatest number of separate bodies, the fluctuations are

* See Appendix I.

best compensated: the equatorial plane of the planet is almost exactly that of its orbit.

Are quantitative conclusions to be drawn from our theory? The very nature of the phenomenon, its statistical character, makes it impossible to give accurate quantitative forecasts for individual planets. If, however, we confine ourselves to rough estimates, some quantitative conclusions are possible. Approximate formulae for the evaluation of the amount of rotational momentum have been proposed by Alfvén and myself and, later, by Lebedinsky and Gurevich. A detailed analysis shows that the type of theoretical formula should depend on the form of concretization of the law of planetary distances. Without citing these formulae—they are still crude drafts—we will confine ourselves to one important conclusion to be drawn from them: they all show that the period of the revolution (the length of the day) should be of the same order of magnitude for all planets.

This is actually the case—all the planets have a period of rotation ranging from 9 to 25 hours, with the exception, of course, of Mercury and Venus whose rotation is partially or fully damped by the tidal action of the nearby Sun. At first glance such small differences in the periods of rotation are astounding when we remember the tremendous difference in mass, density and other features of the planets. The theory, however, foresees qualitatively just this similarity of day length.

Now let us take the origin of the satellites. The satellites are formed in one single process together with the planets. During the process of planet formation, when particles encountered the bigger planet embryos, some of them lost their velocity to such an extent in collisions that they were captured from the swarm and began to revolve around the planets. In this way a condensation, a swarm of particles, was formed near the planet embryo and revolved about it on elliptical orbits. These particles also collided amongst themselves, thus changing their orbits. In these swarms, processes similar to the formation of planets took place on a smaller scale. The majority of the particles fell on to the planet and were absorbed by it, but some of them formed a swarm around the planet and accumulated to form independent embryos, the future satellites. The exception is the ring of Saturn which consists of small particles that have not been able to agglomerate on account of the tidal action of Saturn in whose immediate vicinity they are (an unformed satellite). As the orbits of the particles forming a satellite were averaged, the satellite acquired a symmetrical, almost circular orbit in the equatorial plane of the planet and could not fall on it. In this way satellites appeared around the planets.

Thus we see that the formation of the satellites was a by-product of the formation of the planets. The investigation of the balance of energy and momentum cited above when we examined planet rotation is, therefore, also applicable to the satellites. This gives us the key to an understanding of the different directions in which the satellites revolve. If a substantial part of the kinetic energy of particles captured by the planet is converted into heat by collisions, then the satellites formed from them possess direct revolution. In the vicinity of the growing planet the spatial density of the captured particles is relatively high and collisions during capture are inevitable so that we may expect great losses resulting from the conversion of kinetic energy into heat.

For this reason the rotation of the nearer satellites should be direct, which is actually the case. Even the satellites of Uranus are direct in respect of the rotation of the planet although its rotation is unusual—its axis is inclined at an angle of 98° to the plane of the orbit.

I have proved, for the extreme case when losses of kinetic energy during capture may be neglected in the first approximation, that the satellite so formed should have retrograde motion. The retrograde satellites of Jupiter and Saturn satisfy these theoretical conclusions. The Neptune system is an anomalous one. Its retrograde satellite has a circular orbit and the recently discovered second satellite has direct revolution although it is more distant from the planet than the first. It seems that the second satellite was captured by Neptune ready-made since it is situated close to the plane of the planet's orbit but not in the plane of its equator and the orbit of the satellite, furthermore, is greatly elongated.

* * *

One of the outstanding features of our planet system is the division of the planets into two clear-cut groups: the four nearer to the Sun (from Mercury to Mars) have small mass but great density and the distant planets, from Jupiter to Neptune, are much bigger but consist of material of lower density (see Table 3.) The atmospheres of these giant planets contain methane and ammonia, compounds that are not typical for the Earth. Pluto's mass makes it unlike the other distant planets. It was formed on the outskirts of the system where the material of the protoplanetary cloud approached zero density.

Table 3

Inner planets	Mass (Earth's Mass=1)	Density gr/cm³	Distant planets	Mass (Earth's Mass=1)	Density gr/cm³
Mercury	0.0545	5.5	Jupiter	318.35	1.34
Venus	0.816	5.1	Saturn	95.33	0.70
Earth	1.000	5.516	Uranus	14.58	1.4
Mars	0.107	3.9	Neptune	17.26	2.2
			Pluto	?	?

It is now generally accepted that the small mean densities of the giant planets are due to the fact that they consist of a dense core surrounded by an envelope of incomparably less dense material. There is no reason to believe that the composition of the central cores differs essentially from that of the Earth, except that their density is higher owing to greater pressure in the depths. With regard to the envelopes—some astronomers thought them to be cold and to consist of ice and frozen hydrogen while others believed them to be greatly extended atmospheres. The low temperature of the outer visible boundaries of the atmosphere of Jupiter and the other giant planets should not be allowed to mislead us. There may be high temperatures in the depths of these planets. At the same time we must remember that the tremendous gravity on these planets makes pressure much higher in the depths of the atmosphere. At a depth of 100-200 kilometres below the visible surface all the gases are pressed to a density similar to that of their liquid or solid state.

The sharp difference between the two groups of planets is so prominent that it could not have been ignored. Nevertheless this fact was not explained although some attempts have been made. Jeans, for example, refers to his "cigar." He assumed that the greater part of the mass torn away from the Sun was concentrated in the middle of the "cigar" and that Jupiter and Saturn formed there, while planets of smaller mass formed at the ends. This line of reasoning could, at best, explain the gradual decrease in mass from Jupiter in both directions but it could not explain the sudden jump from Jupiter to Mars.

Partisans of the hypothesis of the "hot" initial state of the planets formed, in some way or another, from solar material, explained the difference in planet density in the following way: if the planets were at first hot there must have been a continuous escape of matter from their outer layers since part of the gas molecules had, on account of the high temperature, sufficient velocity to overcome the planet's gravitation. This process would continue to a lesser degree as the planet gradually cooled down. Different molecules have different velocities but, on the average, the lightest molecules have the highest. The velocity of escape, on the other hand, is greater, the greater the mass of the planet. For this reason the more massive planets, Jupiter, for example, could retain a greater quantity of volatile and light substances than the smaller planets, for example, the Earth. This would account for the difference in density.

Owing to its simplicity this viewpoint gained popularity. Nevertheless it is erroneous.

A gradual escape of gas from the planet atmosphere is a fact that nobody disputes. It is also true that the escape is greatest from the less massive of the planets. In particular: the helium that is produced by radioactive decay on the Earth, or the hydrogen that is produced in small quantities by certain geochemical processes, cannot accumulate in the Earth's atmosphere. For reasons mentioned above the Moon could not retain an atmosphere. The question now to be answered, however, is a different one: could such light gases as helium and hydrogen have escaped from the Earth if its original composition had been the same as that of the Sun, i.e., if hydrogen had dominated over all other elements and helium had been second to it in quantity?

This problem was correctly studied theoretically by Shklovsky. He showed that thermal dissipation cannot, in a cosmogonically acceptable period, produce a noticeable decrease in the mass of a gas condensation that is held together by its own force of gravity. Thermal dissipation, therefore, cannot account for the present composition of the terrestrial planets.

In this connection it is worth while remembering a recently discovered fact, the presence of a methane atmosphere on Titan, Saturn's satellite; Titan is similar to the Moon in mass but is similar to Saturn itself in the composition of its atmosphere.

The Earth's hydrogen deficiency is not due to the gas having escaped but to the simple fact that it never had much—the Earth was formed from material that from the very beginning contained very little hydrogen. Now we shall explain in greater detail the difference in the conditions under which the two groups of planets were formed.

According to our cosmogonic theory the division of the planets into two groups is the result of the Sun's influence on the surrounding gas-dust cloud. A number of factors were involved but the most important of them was the heating of particles to different degrees by the Sun's radiation which led to an absence of frozen volatile material in the composition of the particles that were heated.

In 1948 B.Y. Levin noted that the chemical composition of meteorites that fall to the Earth had created a wrong impression of the composition of small solid particles existing in other regions of the universe—all of them are regarded as being stone or iron. Actually the most abundant chemical elements in all parts of the universe are hydrogen, helium, carbon, oxygen and nitrogen. When molecules are formed from atoms the most abundant compounds to be produced are CH_4, NH_3, H_2O, CO_2. (Helium is chemically inert.) Solid condensations of these gases may form separate particles or form part of compound particles together with iron and stony substances thus making them like dirty ice. In the primary cloud solid particles in the regions near the Sun could not have retained ice, methane, ammonia, carbon dioxide, etc., in their composition since these substances would all have evaporated. The temperature set up by solar radiation on Mercury's orbit is about 600°K, on the Earth's orbit about 300°K. The easily fusible compounds mentioned above would not have been retained in a solid state at such temperatures and, owing to the low pressure in the cloud, they could not have been retained as liquids. Levin noted that the evaporation of condensations of ammonia, carbon dioxide and water must have taken place somewhere near the boundary between the region of the giant planets and that of the terrestrial group.

The role of the flattening and condensation of the dust component in the division of the planets into two groups has been shown by Gurevich and Lebedinsky. These authors noted, amongst other important results of the evolution of the cloud, the opacity of the dust disc, beginning at some distance from the Sun. Up to this distance, coinciding approximately with the asteroid belt, the Sun's heat is appreciable but beyond that boundary, in the zone of opacity, the temperature is close to absolute zero. For this reason gases in the distant regions will condense and freeze on to dust particles and those in the nearer will gradually move into the outer regions. The nearer regions of the dust disc in the protoplanetary cloud, therefore, are constantly being deprived of volatile compounds. This creates zonal differences in the composition of the cloud due to physicochemical causes. From what has been said we can draw an important conclusion. In analyzing the general physical properties and composition of the Earth and other planets we should not regard the composition of solar gas as being that of the original material, but should start from the properties of the protoplanetary cloud, the composition of its particles at that distance from the Sun at which our planet and others were formed.

A small inner zone near the Sun was heated by its radiation so that here only particles of non-fusible stony matter and metals with high density could exist; these were the materials from which the terrestrial planets were formed. In the huge outer zone, shut off from influence of the Sun's rays, the temperature of the particles was so low that volatile substances froze on to them—water vapour, carbon dioxide, methane, ammonia and related compounds. In the composition of these planets, therefore, the light components predominate and their densities are low.

In the case of the transparent space a computation of the equilibrium temperature of a black or grey body at a distance of R astronomical units from the Sun gives the formulae

$$T = \frac{277°\mathrm{K}}{\sqrt{R}} \text{ and } T_1 = \frac{393°\mathrm{K}}{\sqrt{R}} \qquad (8)$$

The first formula is for small bodies that are heated right through (dust particles, for example) and the second applies to the centre of the illuminated hemisphere of bigger bodies (for example, an asteroid or planet without atmosphere) in which the heat received from the Sun does not have time to penetrate right through the body but is radiated directly from the places on which it falls.

Now let us examine the temperature of the cloud's particles at those stages of its evolution when space can be considered transparent. Applying the first formula to solid particles in the region of the Earth's orbit ($R = 1$), we see that their temperature had to be more than 0°C., so that such widespread volatile substances as methane and ammonia could not freeze on to them and would be in a gaseous state. At Jupiter's distance the temperature was —150° C., and the above-mentioned light compounds either froze on to solid particles or slowly evaporated, according to their partial pressure. At that stage of the cloud's evolution when the opaque dust disc formed in it, the distant parts were screened off from the Sun by the nearer parts and the temperature of particles in these zones could be as low as 3° K. At such low temperature the light volatile substances were not only retained in the composition of the dust particles in the distant parts of the cloud but they froze on to them, forming a frost layer.

The degree of evaporation (or, on the contrary, congealing) of ice at various distances from the Sun, therefore, depends on the temperature at any specific distance and on the transparency of the dust disc.

There are deviations from the cosmic distribution of elements in the chemical composition of the Earth that show directly that the Earth's composition is not due to dissipation but to the Earth's formation exclusively from solid matter. The very low nitrogen content of the Earth as compared with the oxygen content cannot be explained by dissipation since the two gases have approximately the same atomic and molecular weight. It can, however, be understood when we remember that stony matter is formed chiefly from oxides of the silicates and metals and that chemically passive nitrogen is almost completely absent in them.

Still less understandable, from the standpoint of dissipation, is the tremendous deficit of heavy inert gases, even such heavy gases as xenon and krypton. This deficit, however, becomes perfectly natural when we take into account their absolute chemical inertness, their inability to enter into the composition of solid bodies. The latest data tell us that not only helium and argon but also all the other inert gases present on Earth have been formed by radioactive processes.

Formerly artificial models of the giant planets were proposed in which the hydrogen content was underestimated. The work of Ramsey, Fesenkov, Masevich, Kozyrev, Abrikosov and Kozlovskaya had done much to clear up this question.

According to Kozlovskaya's calculations the hydrogen content of Jupiter is between 70% and 90% of its mass, that of Saturn between 50% and 70%, while Uranus and Neptune have between 15% and 20%. We can point to two possible explanations of the high hydrogen content of the giant planets: 1) as we have shown, the temperature of the particles in the outer zone may have been so low that the freezing of hydrogen can be admitted; 2) during the last stages of the growth of the giant planets an important role might be played by the process of capture resulting from inelastic collisions in which not only dust but also gas was accreted. Although there is good reason to admit that the growth of the giant planets is partially due to gas, we must deny this persistently in respect of the terrestrial planets.

In 1946 I indicated another factor that leads to the parts of the swarm nearer to the Sun becoming deficient in particles. It is known that light pressure gives rise to radiative drag (the Poynting-Robertson effect). It works in the following way. During the motion of particles about the Sun the aberration of light sends the light pressure slightly ahead of the particle instead of along the orbital radius. For this reason its movement is slightly checked, the particle gradually loses its angular momentum and approaches the Sun in a spiral orbit until it evaporates and joins the Sun's atmosphere.

Apart from the particles that fell on the Sun as a result of this radiative drag those particles also joined it whose orbits had become so elongated that in the perihelion they passed near the Sun.

When particles fall on the Sun (i.e., merge with its atmosphere) they bring their orbital momentum with them. As the angular momentum must be conserved, the Sun would acquire rotation about an axis approximately perpendicular to Laplace's plane of the planetary system (if the number of particles falling on the Sun were great enough). Actually the equatorial plane of the Sun is inclined to the ecliptic by only 7°. The Sun's present-day rotation could be explained by the above-mentioned cause. Here we must make the proviso that it is possible that the Sun could have rotated before the appearance of the gas-dust cloud around it. We cannot, therefore, state with certainty that the only cause of the Sun's rotation is the transfer of the momentum of the particles captured from the swarm.

* * *

The factors described above that led to the division of the planets into two groups also explain the origin of the belt of asteroids, a peculiar phenomenon of our planetary system.

Asteroids are small planet-like bodies ranging in size from hundreds of kilometres to a kilometre or less in diameter, descending in an uninterrupted sequence to bodies of the order of meteorites in mass.

The asteroids move round the Sun on orbits mostly between those of Mars and Jupiter (97 per cent of them) and are usually regarded as bodies that fill in the gap in the Titius-Bode law of planetary distances. Olbers' hypothesis that the asteroids were formed by the explosion of a "normal" planet that once existed between Mars and Jupiter, is still current today despite its having no sound foundation.

Some time ago Fesenkov made an attempt to revive the Olbers' hypothesis by suggesting that the planet that gave birth to the asteroids had an extremely eccentric orbit and during one of its revolutions passed so close to Jupiter that the latter's gravitation reduced the pressure in the interior of the planet causing a sudden rise in temperature followed by an explosion.*

This modification of the Olbers' hypothesis, however, is in contradiction to a number of facts. In the first place the orbits of the planets are not greatly eccentric but are nearly circular; this is quite legitimately due to the formation of the planets by the accumulation of numerous smaller bodies. In the second place the effect of Jupiter's gravitation could not cause an explosion since the adiabatic expansion of planet matter is accompanied by a decrease and not an increase of temperature. And thirdly, the variety of asteroid orbits cannot be explained by a single explosion.

The endeavour to trace the origin of the asteroids in a single, comparatively big planet could to some extent be understood if we recall the researches of Roche and later of Jeans who showed the impossibility of the formation of small bodies from a gas medium. Now that it has been explained that the planets were formed from a gas-dust medium and it has been proved that the formation of bodies of asteroidal size out of that medium is also possible, there is no reason to insist on the hypothesis of the formation of asteroids by means of an explosion or disintegration of a mother planet.

In the light of our theory of planet origin there is no need for any special hypotheses of the origin of asteroids since their peculiarities arise out of the general regularities established by the theory.

* V. G. Fesenkov has changed his views recently (cf. *Astronomichesky Zhurnal*, Vol. 33, No. 5, 1956). On the basis of a detailed study of meteorite data he has come to the conclusion that the asteroids were formed simultaneously with the planets out of the same protoplanetary medium.—*Ed.*

The orbits of the majority of the asteroids lie in a belt at a distance of about 2.8 astronomic units from the Sun. According to the first of the formulae cited above (8), the temperature of the particles in transparent space is close to —100°C. Where temperatures were still lower, as they were at the opaque disc stage, methane and ammonia could be solids in the form of ice, so that the composition of the solid particles in the asteroid region was similar to that in the region of the giant planets. The second formula, however, must be applied to the bigger bodies formed by the aggregation of small particles. For the distance $R = 2.8$ this formula gives us $T_1 = -38°C$. This means that, although at one time ice particles could have existed in the asteroid zone, when they accumulated to form bigger bodies they must have begun to evaporate so that the bodies now in that zone can only contain substances with a high melting point, as is the case with the Earth, but with the possible addition of larger quantities of water. From the standpoint of the formation of big bodies, the asteroid zone belongs to the region of inner planets that has become poor in solid matter that might enter into the composition of such bodies. If a single planet had been formed there it would have been a small one, like the Earth or Mars, and not like Jupiter.

A single planet, however, could not have formed there. The process of planet formation in that zone was checked at the intermediate stage of smaller bodies. This was due to the proximity of massive Jupiter and the above-mentioned temperature and compositional peculiarities of the bodies formed in that zone.

The formation of planets begins with the appearance of numerous bodies of asteroidal size (planet embryos) that grow by the accretion of particles and are splintered by collisions. The peculiarities of the process of growth, reflected in the law of planetary distances, do not allow the formation of two large bodies moving close to each other on complanar orbits. Even in the early stages of the evolution of the protoplanetary swarm, perturbation caused by the growing Jupiter must have been considerable and have influenced the movement of bodies forming in the asteroid zone, increasing the eccentricities and inclinations of their orbits and thus preventing their accumulation. When bodies are in motion along slightly elongated and slightly inclined orbits their rate of growth is greater than their rate of loss. But when the eccentricities and inclinations of the orbits are increased the process of break-up begins to predominate.

The borderline position of the asteroid belt, owing to which the changes of temperature in the particles during their accumulation into larger bodies are accompanied by changes in their chemical composition, made it easier for Jupiter's perturbations to have their effect. The evaporation of volatile substances from forming bodies would either lead to their disintegration or would make them more friable so that they would easily break up in collisions. In this way evaporation slowed down the process of the formation of large bodies in the asteroid belt and Jupiter's perturbations had time to change the orbits of the bodies.

The total mass of the asteroids today is estimated at 10^{-3} of the mass of the Earth. The splitting of the asteroids (as a result of collisions with one another and with meteoric bodies) and the fall of small bodies on the Sun (as a result of radiative drag) leads to a continuous decrease of the total mass of all asteroids which, in the past, was greater than it is today. There is, however, every reason to suppose that it was never very great. Firstly, massive Jupiter swept up particles flying into its zone from neighbouring areas, thus denuding them. Secondly, by disturbing the motion of bodies and particles travelling in the asteroid zone, Jupiter prevented their accumulation so that radiative drag had time to make itself felt and shift smaller particles out of the asteroid zone toward the Sun.

The important role played by these factors in the asteroid belt may be judged by the fact that even in the Mars zone which is much farther from Jupiter, the influence of the massive neighbour is appreciable and Mars' small size is due to this.

The asteroids, therefore, are not the result of an explosion or the disintegration of a big planet but are bodies whose formation in the preplanetary swarm was stopped at the intermediate stage owing to their region lying on the boundary of two planet families of different composition and different mass and was then reversed—splintering and destruction predominated where formerly there had been the uniting of particles and bodies.

* * *

We know that comets were, for a long time, the most mysterious of the heavenly bodies. The great difference between their motions and that of the planets, and the presence of the luminous tails led people to believe that they were of quite different origin from the planets. Kant was the only scholar who linked up all the bodies of the solar system in a single process, assuming, in particular, that the comets were formed at the same time as the planets but on the outskirts of the cloud from which the entire system was formed.

The elongated shape of the comet orbits led Laplace to postulate the coming of the comets from other worlds, alien to the solar system. It was also assumed that their passage close to the planets might have changed some of their orbits to elliptical. Data obtained by observation did not provide one single indubitably hyperbolic orbit.

Another group of hypotheses connects the origin of the comets with certain later processes within the solar system, such as the splintering of planets or asteroids. The chief argument is the thesis of the short life of the comets. This thesis is based on the following observations: 1) the brightness of the short-period comets is reduced when they make repeated transits through the perihelion; 2) some comets have disintegrated, giving rise to meteoric streams. These data are indisputable. We must not forget, however, that those comets are short-lived whose perihelia are close to the Sun. A body of the same composition as the comets but whose perihelion is more than two or three astronomical units from the Sun, has no tails. It is absurd, however, to assert that bodies of the comet composition, including those with elongated orbits, must pass close to the Sun and cannot have perihelia that are more than three astronomical units away. Only those bodies of comet composition are "short-lived" that have been brought on to orbits of short period with perihelia close to the Sun (because of planet disturbances or for other reasons). The question of the nature of the comets and their origin cannot be decided on the basis of temporary and local conditions alone.

We know that the brightness of the heads and tails of comets is due to gases emitted from the comet nucleus when it is heated by the Sun. Comet spectra show molecules of C_2, CN, CH, OH, CO, N_2. They are apparently the product of the disassociation of the more complicated molecules of CH_4, NH_3, H_2O, CO_2 and others. But where do these gases come from? It was formerly believed that they were gases that had been sorbed by the solid, stony or metallic matter of the nuclei. Recently, however, it has been shown that gases sorbed by the nuclei could not be sufficient for repeated ejections of the observed intensity. It has to be admitted that the volatile substances exist in their frozen form, as ice particles of various composition, and that they constitute a very large part of the total mass of the comet. In 1950 Whipple published an ice model of a comet nucleus. In agreement with an earlier work by Dubyago, this model provides an explanation of the secular deceleration or acceleration of motion observed in some comets.

In cases where the comet approaches the Sun (perihelia of less than three astronomical units) part of the ice evaporates, sometimes very intensively. Complete evaporation is prevented by the non-volatile matter contained in the nuclei in addition to the ice (dust and bigger particles of matter with a high melting point): as the ice evaporates a protective crust of petrean matter remains on the surface and slows down further evaporation so that the ice is sufficient for a number of revolutions. In the end, however, the whole of the ice evaporates and the comet ceases to emit gas. At the same time the evaporation deprives the solid particles of the "cement" that holds them together, the nucleus of the comet becomes more friable and it is more liable to disintegrate under the impact of shocks from passing meteorites or by the sudden powerful evaporation of the remaining ice causing a rocket-like emission of gas that tears the parts of the nucleus asunder. In the end the comet is fractured and gradually turns into a stream of meteoric bodies with orbits close to each other. But how did the ice first form?

We must get rid of the fallacious method of inventing a separate cause for every separate phenomenon instead of examining all the various phenomena of the solar system as a single process. All similarities and differences should be due to the natural evolution of the system.

As we have seen one of the important intermediate stages in the evolution of the cloud was the formation of a swarm of bodies small in size. The composition of these bodies depended on the temperature at the places where they were formed. In the outer zone of the dust and gas cloud they were ice bodies mixed with dust. These were the "bricks" from which the giant planets were gradually built up. Some of these "bricks" did not have time to enter into the composition of the planets and remained as separate bodies.

Which of these bodies had the greatest chance of escaping union with the planet and retaining its independence? In the course of the evolution of the cloud, during the process of the formation and growth of such bodies, they not only collided inelastically but also approached each other without collision. In such cases, bodies that possessed sufficient mass changed their orbits under the influence of mutual gravitation. Some of the perturbed orbits became huge ellipses with high eccentricity and great inclination. Bodies possessing such orbits had the greatest chance of surviving since they rarely approached the plane of symmetry of the system where density was greater and where the planets were formed; they had, therefore, less chance of merging with the planets.

The orbits of the comets do not remain unchanged, and there are many causes bringing about changes. Firstly, when a comet passes near a planet, especially a massive planet such as Jupiter, it is certain to have its orbit affected in some way. It may happen that a long-period comet may be transferred to the category of short-period or vice versa. There can also be a transition to a hyperbolic orbit which would lead to the escape of the comet from the solar system. Secondly, the orbits of the so-called quasi-parabolic comets go far beyond the limits of the planet orbits and some of them might come under the gravitational influence of other stars; this influence may change the orbit somewhat, for example, it may bring the perihelion closer to the Sun, i.e., make the comet visible. Thirdly, as the comet approaches the Sun there is an escape of gas and even a partial disintegration of the comet. In such a case the orbit changes, sometimes appreciably.

The first and second causes have long been known and have frequently been used for certain theoretical constructions and the third was proposed by A. D. Dubyago (in part it was proposed earlier for the comet Enke).

The comets, therefore, are not some sort of specific, rare bodies but are a form of matter *typical* for the intermediate stage in the development of the planetary system. The comets are living witnesses of that intermediate stage. The composition of comet nuclei is a direct indication of the existence of solid condensations of light substances of protoplanetary material that constituted a considerable part of the solid phase.

* * *

The two groups of planets that are distinctly different in their chemical composition had two corresponding groups of smaller bodies—the comets formed in the cold outer zone of the cloud and the asteroids formed on the boundary between the inner and outer zones. The ice nuclei of the comets help us understand the composition of the embryos of the giant planets and their satellites. Asteroids are linked in a continuous transition with still smaller meteoric bodies, including the meteorites that fall on the Earth. Fragments of asteroids, the meteorites, with their chondritic and sometimes brecciated structure, help us to understand those frequent splitting and accumulation processes that take place at the early stage of the evolution of the cloud.

The solid particles were the building material from which the bigger bodies were built several thousand million years ago, but the solid particles that are now present in interplanetary space are the product of the disintegration of some of these bodies. The remains of the "primary" particles of the terrestrial zone have long since fallen on to the Sun as a result of the Poynting-Robertson effect. The majority of the presently existing interplanetary particles are the product of the disintegration of small bodies in the solar system in which bodies the substances they are composed of have spent several thousand million years.

The evaporation of comet ice and the liberation of solid particles with a high fuse point enclosed in it, the collision and splitting of asteroids—these are the processes that keep solid particles in the interplanetary space at the present time, particles that we observe in the form of meteors or zodiacal light. Both these sources of meteoric bodies have been indicated before but they were said to be opposed to each other; we believe that both of them exist together. It is theoretically possible that amongst the meteoric particles some remnants of the original cloud may have been retained, although they most likely constitute a very small part.

The minor bodies of the solar system lost their ability to increase their size a comparatively long time ago. A period of predominant splitting has come for them and it will last for a long time. The majority of the fragments join the Sun. A small portion of them falls to the Earth and the other planets, thus, in a way, continuing their increment.

* * *

I must stress that the theory of the formation of planets from the dust and gas cloud outlined in this lecture and the explanation of all the fundamental features of the solar system are logically independent of the hypotheses of the origin of the cloud. Once there was a gas and dust cloud around the Sun, no matter where it came from, its further evolution was determined by the intrinsic laws of the system—the Sun and the cloud—and had inevitably to lead to the formation of planets.

Without having recourse to additional hypotheses we have explained the fundamental features of the solar system on the basis of simple ideas on the former state of matter and the proved laws of nature. We are convinced that this is a sound way to build up the cosmogonic theory.

Lecture 3.

THE PROBLEM OF THE ORIGIN OF THE GAS-DUST CLOUD

In the preceding lectures we have deduced that the material from which the planets were formed existed, prior to their formation, in the form of a circumsolar cloud of dust and gas: this has been deduced from the simple regularities of the planetary system—the circular complanar orbits and the division of the planets into two groups. By the application of the laws of physics, mechanics and chemistry we reconstructed the evolutionary course of the cloud. This gave us an evolutionary explanation for all the widely known regularities of the solar system, except one—the distribution of the angular momentum. The explanation of this last regularity is connected with the origin of the circumsolar gas-dust cloud.

The earlier the stage of evolution examined the more difficult the research becomes since we have fewer definite facts at our disposal. For this reason and others the question of how the gas-dust cloud formed around the Sun and where it came from still gives rise to doubts and disputes.

The question of the origin of the material from which the planets are formed or out of which they arise is one that all former theories and hypotheses also had to deal with. As a guide to the present situation on this question it will be worth while examining some of them (not all, since that is not my purpose) in order, at least, to establish the chief types and classify the preceding scientific essays in this field.

All existing hypotheses and theories may be divided into three classes according to where the material for the planets is taken from. One class consists of those theories which claim that the Sun and the planets came into existence at approximately the same time and from one single mass that has been given the somewhat indefinite name of the "nebula." To this class belong the Kant-Laplace theory, many other old hypotheses that I shall not mention by name and, of the modern hypotheses, those of Weizsäcker, Kuiper, Urey, the first and third (latest) hypotheses of Fesenkov and others.

In the second group may be placed those cosmogonic hypotheses that take the material for the planets from an already existing Sun. Of the older hypotheses in this class are that of Leibnitz (the volcanic eruption of matter by the Sun) and that of Buffon (the Sun was struck by a comet which broke off a piece of matter); the well-known tidal theories of Moulton-Chamberlin, Jeans and Jeffreys are also of this class although of more recent date—the beginning of this century. Fesenkov's rotation hypothesis may also be placed here.

Lastly, there is the third group of hypotheses that take the material for the planets from interstellar matter after the formation of the Sun. This class includes See's hypothesis, the Alfvén theory, my theory and Edgeworth's hypothesis.

It is clear that no classification can be exhaustive. It could be done in other ways. There are also intermediate, compromizing types. Take the hypotheses of Lyttleton and Hoyle, for example: these hypotheses say that the Sun was originally a component of a double or triple star and later, under the influence of various causes, the planets were formed out of material drawn both from the Sun and another star; this is obviously a complicated mixture of all three classes.

I have mentioned only those hypotheses that have had historic significance or have been proposed during recent years, since I do not intend to go into the history of cosmogony.

An analysis of the mistakes and defects of previous theories is, naturally, very instructive. I shall not do this in detail. The first criterion is this: a theory cannot be accepted if it contradicts the fundamental, well-established laws of nature, such as the law of the conservation of energy or the law of the conservation of angular momentum. It seems that all the hypotheses mentioned in my first two classes, apart from their individual shortcomings, cannot be made to conform to the law of the conservation of angular momentum.

The distribution of the angular momentum in the solar system is very specific and differs very greatly from the distribution of mass. The Sun contains over 99 per cent of the mass of the solar system but has only 2 per cent of the angular momentum, while the planets contain about 1/700th of the mass and 98 per cent of the angular momentum.

How could this have happened? Obviously, the theories of the first class according to which the planets and the Sun were formed from one common mass cannot explain this distribution. There is no mechanism permitting the greater part of the mass to aggregate in the central body while the greater part of the momentum remains concentrated on the periphery. There is no sense in inventing new variants of the Laplace and analogical theories unless that theory or hypothesis is able to explain the distribution of momentum.

The same applies to the second group, that is, to the hypotheses which take their material for the planets from the Sun in some way or another. Again, there is no mechanism by means of which the Sun could have given Jupiter, to say nothing of Neptune, an angular momentum that is enormous in view of the tremendous radius of the orbit. It is a strange thing that the significance of this law of nature, although it had been tested and proved millions of times, seemed to have penetrated very slowly into the depths of astronomy, if I may so express it.

In his book on cosmogonic hypotheses Poincaré did not even mention this argument against Laplace, although it had already been put forward by Babinet and Fouché in the 19th century and See supported it at the beginning of the 20th century. Poincaré quoted Fouché's calculations but did not draw the necessary conclusions from them.

The Jeans theory was wrecked on the same question of the distribution of momentum after the work done by Russel and Pariisky in the 30's and 40's of this century. Jeffreys, who held views close to those of Jeans, himself renounced his theory. Nor does Fesenkov's rotation theory, as the author himself admitted, explain the distribution of the momentum. Later we shall examine the attempt made by V. A. Kraf and Fesenkov to avoid the angular momentum difficulties.

The criterion of the momentum shows us that we have to find the answer in the third class of hypothesis, that is, we have to reject the isolated study of the solar system and bring into our work the whole of the great system known as the Galaxy, the Milky Way. Once galactic material is added to the investigation there is no further difficulty with the momentum since both stars and gas-dust clouds moving within the Galaxy have a tremendous angular momentum in respect of each other and in respect of the centre of gravity of the Galaxy; in distributing this momentum we do not need to stretch a point to get the momentum possessed by the planets, even by those most distant from the Sun.

See realized this at the beginning of the 20th century. According to See the Sun captured the planets from the Galaxy where they had existed previously as independent bodies, as dark spheres. Such a dark sphere, approaching the Sun with hyperbolic velocity, was checked by the resisting medium surrounding the Sun and its velocity was so reduced that it became elliptic. There was, however, no material surrounding the Sun that could have offered such resistance. Apart from that See was unable to explain any of the simplest facts of the solar system that Laplace had explained before him: the circular orbits, motion in one direction and in one plane. For this reason See's hypothesis did not attract any great attention and had no followers although, as we shall see, it contained a valuable and sound element—the idea of using extrasolar, galactic material.

A very valuable idea was propounded by Lindblad in 1935. He stressed the great cosmogonic significance of processes that are going on in the diffused material (gas, smoke, dust) that has a low density but fills interstellar space universally. Lindblad drew attention to the significance of processes going on in interstellar space, the association of molecules into dust particles and then the particles into bigger bodies. He did not, however, develop this profound and valuable idea nor did he give it concrete form.

In 1944 I proposed my hypothesis on the formation of the planets from material captured by the Sun out of interstellar matter. The motions, in respect of each other, of the stars and interstellar gas and dust clouds taking part in the galactic rotation, gave me the idea that the solution to the riddle of the origin of the gas-dust cloud around the Sun was to be found here. If the Sun, passing through a cloud, or near it, could "capture" part of the material and take it with it, the Sun would be surrounded by a cloud out of which the planets could later be formed. If the cloud originated in this way there is no further difficulty with the distribution of the angular momentum. This momentum would result from a redistribution of the angular momentum of the Galaxy; part of the angular momentum possessed originally by the cloud in respect of the passing Sun would be retained by the part of the cloud captured by the Sun.

For our explanation of the origin of the solar system we introduce the material and the forces of the Galaxy. Is this correct? Would it not be more correct to explain the origin of the solar system by the development of the internal forces of the system itself?

The concept of the general interconnection of all phenomena is one of the basic dialectic concepts and is well enough known to all of us. The problem of the relationship existing between the internal and external is solved concretely by materialist dialectics where everything associated with the given phenomena is taken into consideration. Many examples can be quoted when limitation to internal factors alone is an unscientific approach. It would not, for example, be correct to explain the circulation of the Earth's atmosphere without taking into consideration such an outside factor as the heat of the Sun. Any number of similar examples could be given. There is no justification for a theory that limits itself to internal forces in a system that is so closely bound up with its environment as the Sun is with the Galaxy. There is no justification for artificially cutting the Sun off from the Galaxy. On the contrary the environment in which the Sun rotates should be taken into account. That which was formerly not clear in the solar system may now be explained quite simply if we turn to the Galaxy and the motion of the Sun through it. It is this circumstance that makes the "capture" hypothesis so tempting despite the fact that there are some difficulties connected with it which we shall discuss later.

Let us examine the phenomenon of capture more closely. A little later we shall give examples of other types of capture but for the time being will confine ourselves to a description of the phenomenon of capture under the influence of gravitation.

If two bodies are isolated from all other bodies, the motion of one of them relative to the other, under the influence of mutual gravitation, will follow a conic section. If, at any time, the relative velocity has been hyperbolic, that motion can never become elliptical. In the case of two bodies capture is impossible. In the case of three bodies a substantially different picture presents itself to the mind.

Let us suppose that two bodies had, up to a certain moment, hyporbolic relative velocity. Under the influence of a third body that motion may change. The relative velocity of the two bodies may be sufficiently decelerated for the motion to become elliptical. This would be capture. When this happens there is a redistribution, between the bodies, of energy and angular momentum, their sum total, naturally, remaining unchanged. The difference in the energy of the relative velocity, hyperbolic before capture and afterwards elliptical, will be taken over by the third body whose velocity will change accordingly.

Is capture possible in the presence of three bodies? This is one of the basic questions in the famous problem of three bodies that has been intensively studied, especially by Poincaré and his followers at the end of the last century. During the 19th and 20th centuries the majority of astronomers and mathematicians grew stronger in their conviction that capture was impossible in the problem of three bodies. Even those who were uncertain thought that capture would be a phenomenon of such rarity that it could have no significance in cosmogony.

Astronomers first became interested in the problem of capture when dealing with the possibility of Jupiter's capturing an asteroid and turning it into a satellite. In this case we have the Sun, Jupiter and a third body so small in mass that the motion of Jupiter is not appreciably perturbed. This produced a scheme, given the name of the restricted problem of three bodies that has been studied since Jacoby's day. The impossibility of capture in this scheme was shown by Zeipel and Hopf.

What shall we get if we reject this artificial construction and examine in a general form the motion of the three finite masses? In the general problem of three bodies the impossibility of capture was shown by Chazy's work on the asymptotic character of motions. In 1929 he published an investigation of the case when the constant of the energy integral $H<0$, and in 1932 for the case when $H>0$. The second paper did not contain a strict proof, which remained undetected by scientists.

These investigations, as well as the fact that students in this field are accustomed to the restricted problem with its extensive literature, created the impression, as we have said, of the impossibility of capture, so that for practical purposes capture was excluded from the arsenal of cosmogonic studies. In Nölke's book, published in 1919 and widely known in its time, all possible cosmogonic schemes are pedantically outlined, but capture is abandoned from the very outset as being impossible.

Despite this state of affairs my conviction in the physical possibility of capture led me to begin work on the elaboration of cosmogonic theory that assumed this possibility although at that time I had no proof of it. In 1947, however, I succeeded in answering the question and produced an example of capture in the problem of three bodies. The equations of the motion of the three bodies with predetermined initial data were integrated by numerical methods.

It is, of course, very difficult to choose initial conditions in such a way that motion is certain to lead to capture. Here I was helped by a simple consideration that surprisingly enough had not previously been used. The equations of celestial mechanics are such that they permit a change in the direction of time. The mathematical investigation of motion leading to capture, therefore, is the same as that of the disruption of a system of two bodies under the influence of a third. It is, however, much easier to choose initial data for the latter.

I went to work in this manner. I examined the motion of three bodies of equal mass moving in one plane. The initial data were selected to make the case a typical one for binary stars both in their relative orbits and their velocity. The initial data for $t = 0$ are: the undisturbed orbit of P_1 under the gravitational influence of P_0 was an ellipse with a major half-axis equal to 200 astronomical units (a period of 2,000 years) and its eccentricity 1/2, while the undisturbed orbit of P_2 is hyperbolic. Using these initial data computations were made both backwards and forwards in time.*

Fig. 1 (See p. 88.) shows the trajectories of bodies P_1 and P_2. As can be seen from the diagram, one of the bodies, describing an elliptical orbit, makes a sharp change of the direction of its motion when a third body passes close to it—almost a break—after which the second body recedes into infinity. If we examine the motion in the reverse direction then the interaction of the two bodies approaching each other from infinity is such that one of them continues into infinity while the other enters an

* See Appendix II.

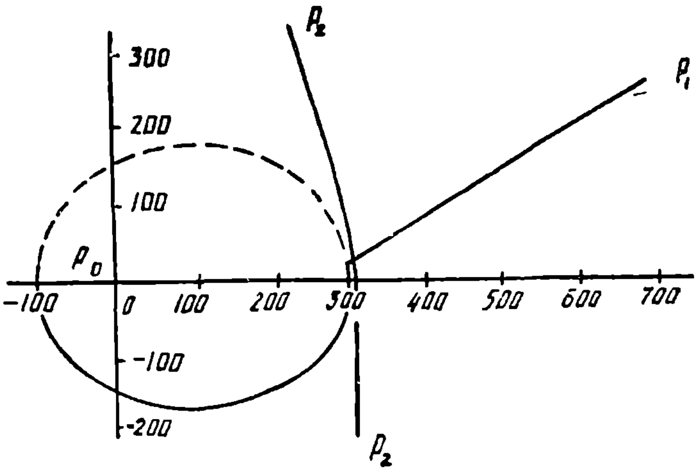

Fig. 1.

elliptical orbit about body P_0, that is, there has been capture. Although this is a single example it has decisive importance like every example that refutes a fallacious general statement.

From the astronomical point of view, when studying the phenomenon of capture, there is no need to follow the movement of the bodies to infinity. Under real conditions the isolation of three bodies from the Galaxy is an abstraction that is permissible as long as those three bodies have not separated to distances comparable with average stellar distance. As soon as they have separated sufficiently for their interaction with other bodies of the Galaxy to become noticeable our abstraction loses its value. It is important for the astronomer to know only whether a stable capture without rupture is certain before that distance is reached by the third body. Under these circumstances the example we have computed is ample. From a purely mathematical point of view it is desirable to solve the general problem, studying motion throughout the time axis.

An estimate of the measure of the set of phase-space points, the starting points for movements leading to captures, is of decisive importance: this will be an estimate of the probability of capture. So far we are not interested in quantitative estimate of this probability, but in finding out whether or not the capture will result from the initial data that constitute a set of zero measure. If the initial data leading to the capture fill a whole section of phase space, the measure will be positive.

It follows from the fact of the existence of at least one example of capture on the final time interval, and from the general properties of solutions of differential equations, that a set of initial data leading to capture on the same time interval has a positive measure and not a zero measure. It is impossible to decide by such an inductive method whether this will be true for the general case with an infinite time interval. We are, therefore, faced with the mathematical problem of proving, for the general case, that the capture is effected with a positive and not a zero measure. This big problem was solved by G. F. Hilmy.*

Hilmy and I, therefore, have shown the possibility of capture in the problem of three bodies and the positive probability of capture. This is a result that is of great importance in cosmogony and is also of interest to celestial mechanics.

In the example I constructed, three bodies of solar mass participated. This was done to simplify the calculation. Bodies of any size may be captured, from dust particles to stars. The result—the possibility and positive probability of capture—is true, in principle, for all

* See Appendix III.

masses and for all mass relations. The mutual capture of two stars is, I believe, a possible cause of the formation of binary stars.

The first numerical example for cases of the capture of a small mass—a dust particle—by a massive body was computed by O. A. Sizova (1952). If, for example, the Sun has entered a dust and gas cloud simultaneously with another star and if certain conditions of mutual distance and velocity are fulfilled, part of the cloud will be captured by the Sun.

Investigations into the possibility of capture in the problem of three bodies were continued by G. A. Merman (1953-1956) and K. A. Sitnikov (1953). Merman used the mathematical method proposed by Hilmy and produced some interesting and more perfected criteria of hyperbolic and hyperbolo-elliptic movements of three gravitating bodies. Sitnikov elaborated an example of capture using the analytical method, i.e., without use of a numerical integration of the equation of motion.

The phenomenon of capture in the problem of three bodies gives us a simple example of the way two bodies form a stable, long-lived system due to the gravitational interaction of three approaching, independently moving bodies. Such phenomena, however, are possible with any number of bodies and for some aspects of our theory cases of large numbers of such bodies are of interest. Hilmy, generalizing the theory of capture, studied the general laws in such processes. We shall not introduce Hilmy's somewhat intricate formulae and theorems, but will look at his conclusions.

When bodies are approaching each other from infinity the system possesses an excess of energy which prevents the gravitational association of the bodies. If, however, the exchange of energy due to gravitational interaction is such that some bodies whose kinetic energy constitutes a large part of the energy of the whole system, move away from the others, then the remaining bodies, under certain circumstances, may form a non-dissipating sub-system. The association of one group of bodies in a stable sub-system should be accompanied by the transfer of excess energy to the other bodies that are rapidly leaving the system and, vice versa, the presence of bodies that are rapidly moving away from the system may cause the formation of a stable nucleus in the system. Hilmy summarizes these relations in the following way: "association and dissipation in gravitating systems are different sides of the same phenomena of the gravitational interaction of matter."

Such is the picture of a purely mechanical case, i.e., when the process is due to gravitation alone. Nevertheless the results so obtained give general indications for those cases when, as often happens in cosmogonic problems, the interaction is not purely mechanical. If, indeed, part of the system is not dissipated, then, at the time of the closest approach of the bodies, some physical process must arise to absorb the surplus of mechanical energy preventing association and convert it into non-mechanical energy, that is, there must be dissipation of energy. In such cases there is the gravitational-physical association of material in which the "outflow" of surplus mechanical energy is brought about by physical processes and not through the dissipation of the system.

The gravitational-physical association of matter produces a number of cosmogonic regularities that are inexplicable within the narrow framework of mechanical laws. A lack of understanding of the limits of mechanics was, in our opinion, the source of a number of the insurmountable difficulties that we find in many of the classical hypotheses of planet origin that depended too much on mechanics.

Our work on capture in the problem of three bodies has drawn the attention of other investigators to the problem of capture and new forms have been noted that are not purely mechanical. T. A. Agekyan studied the dynamics of the passage of stars through clouds of dust material and showed that in this case there could be capture because particles lose speed in collisions. Particles passing near the Sun would be attracted by it and would move about it in a hyperbolic orbit so that there would be a region of higher density behind the Sun. Agekyan's calculations showed that, with quite reasonable initial velocities and densities, the area formed behind the Sun would be of such density that collisions between particles would be certain. The collisions would lead to decreased velocities which would change from hyperbolic to elliptic in respect of the Sun: this is capture. Here we have a case in which the surplus kinetic energy is not carried away by a third body but is transformed into heat.

Another form of capture based on light pressure has been demonstrated by V. V. Radzievsky. It is known that light pressure decreases the gravitational attraction of the Sun. Particles of a definite range of sizes exist in which pressure predominates—particles whose radius is of the order of 10^{-5} cm. If the particles are smaller or larger, light pressure will have its effect but gravitation will predominate. It is interesting to note that with a radius of 0.5×10^{-5} cm. the particles are neutral, that is repulsion and attraction are equal.

Radzievsky showed that for particles of such minute size the third body is not necessary if there is light pressure. The basic idea is the following. If particles of the neutral size approach the Sun and come under the influence of different physical influences, they may disintegrate into still smaller particles. The smaller particles, however, are no longer neutral, gravitation now predominates. It may happen that the original particles approached the Sun in a hyperbolic orbit, i.e., with a positive total energy, while the smaller particles produced by disintegration and attracted by the Sun will possess negative total energy, i.e., they will be in elliptical orbits. An instantaneous capture would then take place.

Thus we see that there are various types of capture. The possibility of these various types makes the phenomenon more probable.

One of the results of capture is that the cloud has a total angular momentum differing from zero. This is due to the following cause. If as a result of capture it would be equally possible for streams of gas and dust material to rotate about the Sun in opposite directions, the total momentum would be close to zero, but in such a case planets could not be formed since the collisions between opposing streams would lead to a loss of velocity and the gradual fall of the material on the Sun. Such a symmetric capture is not really to be expected, save as a rare exception. In the case of gravitational capture with the participation of a second star, the presence of the latter already creates assymmetry in respect of the Sun; as far as other captures are concerned (without a second star) we must take into consideration the irregular, fleecy nature of the interstellar clouds familiar to us from observation. It is sufficient for the Sun to pass through an area with irregularly distributed density, to one side of the centre of a local condensation, for example, for it to capture more particles from one side than from the other and cause the captured cloud to rotate in a dominant direction, i.e., to have angular momentum that differs from zero and, in the general case, is considerable.

The inevitable question arises—how often can capture take place, in other words, what is the probability of capture? The passage of a star through a cloud is not a rare phenomenon: it has been estimated that the Sun passes through clouds on about a thirtieth of its way through the Galaxy. For capture in its classic form, however, the simultaneous passage of a second star in close proximity is essential (for other forms of capture this is not essential). The passage of two stars in close proximity is a much rarer phenomenon. It must not be thought that they have to be very close for capture to be effected. According to the Jeans hypothesis, for example, the passage must be quite close to the Sun (a distance of a few solar radii). For the acquisition of dust and gas materials such as the planets are made of, distances 10,000 times greater may be effective and this increases the possibility of stars encountering one another by 10^{12} times. The phenomenon, however, is still a rare one, especially in view of the fact that capture requires certain velocity restrictions.*

The capture of material may be effected at any stage of the Sun's evolution. Its probability depends to the greatest degree on the state of the Sun's environment at the time of the capture. Under conditions obtaining at present in the Galactic environment of the Sun the probability of capture is very remote. On its way through the Galaxy, however, the Sun has passed through greatly different conditions, amongst them being the passage through clouds of greater density; at earlier stages of its evolution the Sun had greater opportunities of encountering such an environment.

The effectiveness of the capture, i.e., the quantity of captured material, depends on the density of the dust medium in the given area. Obviously the denser the

* This paragraph has been taken from one of the author's manuscripts based on his unpublished investigation of the effectiveness of gravitational capture (1951). During the last years of his life Otto J. Schmidt considered the mechanism of capture connected with inelastic collisions of the particles to be the most effective.—*Ed.*

cloud the more effective will be the capture. The probability of capture in its classical form depends on stellar density and, more particularly, on the distribution of the relative velocities of the stars: the smaller the relative velocity of the stars, the more frequent the capture. In galactic star clusters we have relative velocities of the order of 1 km. per second and even less, as compared with 20-30 km. per second in the present environment of the Sun. Capture in clusters of stars may occur more often (by several orders of magnitude) than outside them.

In addition to a variety of conditions in different parts of the Galaxy, variety in time is also possible. If the Sun was formed from dispersed material in a medium with greater density and low relative velocities, the chances of the capture of a sufficient mass for a protoplanetary cloud were relatively greater when the Sun had not yet left the medium of its origin. If under these circumstances stars formed in groups the chances of capture within that same cloud would be greatly increased.

Further investigation of the conditions for capture and its probability are however necessary.

* * *

Even though we have proved the theoretical possibility and positive probability of capture as the mechanism producing the protoplanetary cloud, there is still a possibility that at the time the stars were formed there existed conditions favouring other ways of forming a cloud in addition to capture. This cannot be denied in advance. Above we have shown that conditions exist in nature which would permit the formation, by capture, of a cloud from which planets would later form naturally. This, however, only proves that *some* of the planetary systems existing in nature were formed from material acquired by capture but it has not been proved —and we do not claim that it has—that capture, particularly gravitational capture, is the *only* means by which stars acquire material for planetary systems. Today we still do not possess sufficient data to say whether *our own* planetary system had its origin in a cloud that was formed by capture of by some other unknown means. It has only been proved that it *could* have originated through the capture of a cloud and its further evolution. This, of course, is no small step forward in the development of science. The final answer will be given only when we know the origin of the Sun and all the circumstances that attended its inception.

Does it not follow from this that a book devoted to planet cosmogony should end on this note and should wait and see what the astronomers have to say in respect of the origin of the Sun? This, in our opinion, would be an incorrect attitude. The problem of the origin of stars, of course, is quite another problem that does not enter into the subject being handled by this book. Between the two problems, however, there is an intermediate area in which we, workers in the field of planet cosmogony, should have a word to say that is based on our planetary studies. We will leave aside the general question of the ways (possibly various ways) in which stars are formed in nature; we are specially interested to know whether there are any ways by which planets could have been formed simultaneously with their stars. To be more precise: during the process of the formation of *our* Sun could *our* planetary system have come into being by any other means than by the capture of the protoplanetary cloud?

The examination of this question is of significance for planet cosmogony and is not without interest for the stellar cosmogony.

There are features in our planetary system that throw some light on the origin of the Sun. These features may be incompatible with certain hypotheses on the origin of the stars. This incompatibility does not indicate that stars could not have been formed in the way proposed by the hypotheses, but it would mean either that our Sun was formed in a different way or that it became surrounded with planet material after its own inception. For example, as B. Y. Levin has shown, the hypothesis that the Sun was formed as a very bright star with a mass 5 to 10 times its present mass and then evolved along the main sequence, is only compatible with our theory of planet formation, as outlined in Lecture 2, if the protoplanetary cloud was captured by the Sun after its mass had been reduced to two or three times its present value.

* * *

There are several hypotheses of how the gas and dust cloud around the Sun came into being but none of them have been elaborated sufficiently to be generally accepted. Apart from the capture hypothesis, the other chief hypotheses are the expulsion of material from the Sun itself and the idea of the parallel formation of the Sun and the protoplanetary cloud.

Some scientists counteract the idea of capture with the idea of the simultaneous formation of stars and planets. They assume that when a star, for example the Sun, was condensed out of diffused material, part of the material beside it could have condensed into smaller bodies that would begin to rotate around the bigger body. The difficulty begins here—why did they begin to rotate? Where did they get their angular momentum from? There is, indeed, no avoiding capture in this concept, either, the only thing being that it must be applied to a hypothetical and still quite unknown initial state. If a condensation is isolated from the diffused galactic material as a result of gravitation and the difference in the galactic angular momentum of its parts becomes a rotational momentum about the centre of the mass, this is the same phenomenon of capture. It seems, therefore, that in the case of "common formation" the appearance of the protoplanetary material is a question of the time and not of the character of the process or its cause. Our theory is broader, it does not offer any restrictions to the time of the capture. The capture of material and angular momentum for the planets could have taken place in the early period of the formation of some of the stars or at any later stage, and may even take place in the present or future. In all cases the formation of the planets takes place in an extended cloud of diffused material with a big angular momentum.

Let us also examine the separation of the protoplanetary cloud from the Sun. If this separation took place in the early stages it is nothing more than common origin, but if it took place at a later stage then the paradox of the distribution of angular momentum between the Sun and the planets is inexplicable.

In order to avoid this difficulty, first V. A. Krat and then V. G. Fesenkov postulated that the Sun was at first much more massive and rotated much faster than at present, so that it would have possessed the very big rotational momentum that is needed. The greater part of its mass was then lost by the so-called "corpuscular radiation," i.e., the ejection of charged atoms out of the stars. As the ejection takes place from the surface, where the specific angular momentum is greatest, the total angular momentum is reduced more rapidly than the mass.

A similar idea was put forward by Tsiolkovsky in 1924. He did not have recourse to corpuscular radiation (it was still not known at that time) but estimated the decrease in mass and angular momentum that would be due to losses caused by normal light radiation (it will be remembered that light possesses mass). Tsiolkovsky took Laplace's scheme as his starting point and computed that a period of time of the order of 10^{31} years would be necessary to bring the hypothetical primordial solar system to its present state! Such a period of existence for the solar system is not feasible in view of the data of modern astrophysics so that Tsiolkovsky's hypothesis could not be accepted and recourse was made to another form of radiation, corpuscular radiation. V. A. Krat expressed only the general idea, without discussing a concrete process and Fesenkov believed that the Sun, losing part of its mass, evolved along the so-called "main sequence." The rate of evolution adopted by Fesenkov required a loss of mass through corpuscular radiation a thousand times greater than through light radiation, although modern data show that it is a thousand times less. V. S. Safronov computed that in the case of the Sun's evolution along the main sequence its original mass would have had to be 150 times greater than its present mass for it to have a specific angular momentum on the equator equal to that of Neptune. But we do not know of the existence of any stars of this size. We have to go farther back, therefore, to the time when the Sun was not a main sequence star. We are then faced with new difficulties, the greatest of which is the complete absence of real facts. The distribution of angular momentum, therefore, is not explained but is relegated to the distant past.

Corpuscular radiation is an interesting subject for research. It is quite possible that it may have some significance for the cosmogony of the solar system as an additional evolutionary factor. The importance of this factor, however, must not be exaggerated. Corpuscular radiation cannot explain the distribution of angular momentum in the solar system.

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As we have already said, the results of the evolution of the protoplanetary cloud outlined in Lecture 2, are logically independent of the origin of that cloud. I believe it to be my duty to point this out, although, at the same time, I am firmly convinced that only the capture of galactic material could have given the Sun a protoplanetary cloud of such great extent and such a huge angular momentum.

Lecture 4.

THE PLANET EARTH

The subject of this last lecture is our own planet, the Earth. It is a subject that includes problems outside the field of cosmogony proper, problems that belong to the sphere of geophysics and geology, and which should, therefore, be dealt with by workers in those fields. For this reason our cosmogonic theory will not, in a number of cases, offer ready-made solutions but will confine itself to formulating questions and communicating new points of view and certain conclusions arising out of the theory which may prove useful in treating problems connected with the Earth.

A cosmogonic theory should not only show the process of the Earth's formation but should also follow up its further evolution to connect astronomical with geological history. This historical analysis of the problem of our planet's origin is the only one that can reveal the forces that are active in the Earth and give geologists, geophysicists and geochemists a new approach to the problems confronting them, a basis for the construction of new theories. The cosmogonic theory, in itself apparently without any practical significance for production, may actually aid the practical workers to build up a correct geological theory on which to develop practical geological survey up to and including prospecting for minerals. The extent to which the sciences dealing with the Earth can take advantage of planet cosmogony depends on the extent to which the latter is able to reveal those features in the constitution of the Earth in its primordial state that conditioned its subsequent development.

Conceptions of the early stages in the Earth's history were always connected with the cosmogonic ideas of the time. Cosmogony has had a very strong influence on the development of the sciences dealing with the Earth. The reverse relationship, i.e., the checking of cosmogonic conceptions by applying the data provided by the sciences studying the Earth, has so far been insufficient. This situation is not due to the level of development reached by those sciences but to the restricted nature of planet cosmogony. The problem of the Earth's origin is a complex one, common to both astronomy and geophysics and its solution requires the realization of a big research programme.

Laplace, one of the founders of materialist cosmogony, was well aware of its significance for the exploitation of geological problems: "The primary gaseous or liquid state that we get to in examining astronomic phenomena," he wrote, "should naturally be manifested in other natural phenomena. In order to reveal it, however, it is necessary to take into consideration the great variety of compounds formed by all the Earth's substances that were in the gaseous mixture when the decrease in temperature made it possible for them to enter into compounds; attention must also be paid to the extraordinary changes that resulted from this decrease in temperature inside the Earth and on its surface—in all its parts, in the structure and pressure of the atmosphere, in the ocean and in all bodies that it contained in solution. The abrupt changes, such as great volcanic eruptions, must also be considered; at certain epochs these must have disturbed the regularity of the changes. Geology, studied from a point of view that brings it closer to astronomy, may gain in precision and reliability in many questions."

The subsequent development of science showed that this was an historical prediction. Laplace's hypothesis appeared towards the end of the 18th century and in the thirties of the 19th century the first scientific geological hypothesis appeared—the so-called contraction hypothesis. In essence it was directly engendered by Laplace's conceptions. With this conception, too, are connected the later geochemical concepts of the zonal distribution of the chemical elements in the Earth.

Many 19th-century geologists stressed the connection between geological and cosmogonic concepts. The geologists of the 20th century, leaving aside all cosmogonic concepts, simply started out from the idea that the Earth was at one time a molten, fiery body.

It is, of course, impossible to build up a theory of the Earth's development without some sort of viewpoint regarding its origin. It is natural that the view taken by geologists on the origin of the Earth should be formed under the influence of the theories dominant in astronomy. But it is a bad thing that this process of mutual relationship often has a time lag. In astronomy the Laplace hypothesis had been proved incorrect by the beginning of the present century, but its influence remained in geology for a long time and is to be seen in the works of some writers today.

On the basis of the theory of the Earth's origin as expounded in the preceding lectures, we shall quote a number of deductions concerning processes taking place in the Earth, the character of its evolution, the rate of evolution and the forces functioning in the Earth. We shall not regard the Earth as a body whose evolution is completed but as a living body whose development continues.

In this lecture we shall examine the following questions in sequence: the length of time taken for the formation of the Earth, the temperature conditions under which the process took place and the role of heat produced by radioactivity in the further history of the Earth, the chemical composition of the Earth and its comparison with the other planets and the Moon, questions of density and pressure, the origin of the seas and the atmosphere, the stratification of matter in the Earth, the further evolution of the interior of the Earth at the geological and modern epochs and the forces acting within the Earth; we shall also touch on the application of the above-mentioned to the question or deep-focus earthquakes and the question of the cause of the formation of mountains.

The Earth, like all other planets, was formed by the collection of separate small bodies and tiny particles. This process was at first stormy and intense but it speedily grew weaker as material in the protoplanetary cloud became exhausted. In the period of geological history it has almost ceased. We say almost, because the penetration of meteorites into the Earth's atmosphere and their falling on the surface of the Earth is, actually, a process of growth, although an extremely slow one that has been somewhat changed by the subsequent evolution of the cloud. During the past two thousand million years a layer only a few centimetres thick has fallen so that it is no wonder if we cannot give direct proof of the formation of the Earth from meteoric matter.

In 1945 I published a paper containing a mathematical analysis of the rate of accretion of the Earth's mass. For convenience of mathematical treatment some simplifying suppositions were introduced; in particular we neglected, in our first approximation, the dynamic influence of the Earth's mass and confined ourselves to calculating the intersections of the paths of the meteorites and the Earth. With these assumptions the following equation was evolved:

$$dm = \frac{2r^2}{R_2^2 - R_1^2}(Q - m)\frac{dt}{P}$$

where: m and r are the mass and radius of the Earth at the given moment; Q is the mass of the material in that "ring" (annulus) of the protoplanetary swarm that went to form the Earth as has been explained in Lecture 2; R_1 and R_2 are the distances of the boundaries of that ring from the Sun; P is the period of the Earth's rotation (the year). A solution of the equation gives us the following:

$$AT = -\frac{1}{3}\ln\frac{\Delta}{3Am_T} + \frac{1}{2}\ln 3 + \frac{1}{\sqrt{3}}\frac{\pi}{6}$$

where T is the age of the Earth, i.e., the time elapsing from the beginning of growth to the present day; m is the present mass of the Earth, A, a constant depending on the present radius of the Earth and former constants, and Δ, the mass of meteoric matter falling on the Earth per annum at the present time.

The above equation shows that the process was at first a very rapid one. Half the mass of the Earth had formed in less that 1,000 million years. Then the process slowed down until today there can remain only tiny remnants of the matter in the Earth's "ring." Tiny particles from the region of the Earth have been long since decelerated through radiation pressure and have fallen on to the Sun. Their place has been taken by particles that formerly revolved farther from the Sun and are now approaching the Earth but for the same reason they will gradually disappear from our vicinity. At the same time bigger bodies, on account of the perturbation of their orbits, will fly into "foreign" regions. For this reason those meteoric bodies that now fall on the Earth are not necessarily remnants of that specific ring that provided material for the formation of the Earth.

By substituting numerical values I obtained, in 1945, the figure 7,600 million years as the age of the Earth. In my calculation I took Δ to be a ton a day. Later estimates show that this mass must be increased to 100 tons which gives us the age of 6,300 million years.

In view of the simplification which we permitted in the solution of the problem we, naturally, do not insist on any definite figure for the age of the Earth but it is important that we get a figure that is of the same order of magnitude as the age of the Earth's crust determined by an analysis of the products of the disintegration of radioactive elements.

Here it must be stressed that the meaning of the ages obtained by radioactive methods depends on cosmogonic conceptions. From the standpoint of the hypothesis of the originally molten Earth, the process of the formation of Earth's crust was of such short duration that the age of the Earth practically coincided with the age of the crust. If, however, we consider the picture of the long-term formation of the crust that we get from the cold beginning of the Earth (we shall have more to say about this below), then not only does it become impossible to speak of the ages of the Earth and its crust coinciding, but the very conception of the age of the crust becomes very indefinite.

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Now let us look at the temperature conditions, in other words, at the thermal history of the Earth. The majority of cosmogonic theories suggest a molten or even a gaseous state for the Earth after its formation.

This is undoubtedly a remnant of the former concept of the origin of volcanoes, a remnant of the concept of the Earth as a molten body with a thin crust through which molten matter from the interior is sometimes erupted. Geophysical data, however, especially the study of the propagation of seismic waves, have long since proved that the deep interior regions of the Earth cannot be in a completely molten state. The discovery of radioactive disintegration and a calculation of the heat which it gives off into the Earth showed, already at the beginning of the century, that it is sufficient to heat up the interior of the Earth and, in some places under the crust, to melt the rocks, so that there is no need for the molten state of the primary Earth to account for the streams of lava. Nevertheless, belief in a formerly molten Earth still holds its own for people are used to it and it is difficult to get rid of it. It would seem that the discovery of radioactivity should have immediately reversed the thermal history of the Earth. But the concept of the gradual cooling of the Earth from an original molten state had become so deep-rooted in science that, in order to retain it scientists agreed to accept an extremely artificial assumption that the radioactive elements are present only in the Earth's crust and are completely absent in the Earth's interior.

In view of this it is important to note that some of the leading representatives of Russian science, such as F. A. Bredikhin and V. I. Vernadsky raised objections to the predominant views. Bredikhin believed that it would be more correct to explain volcanism and other thermal phenomena in the Earth's crust as local processes—"electro-chemical," as he called them—and not as vestigial manifestations of primary heat. In the seventies of the last century there was nothing more to be said so that this was the foresight of a genius who realized that a new source of heat would be found, foresight that was justified by the discovery of the radioactive heating of the Earth.

Vernadsky dealt with this question on several occasions. In his *Notes on Geochemistry*, for example, he wrote: "All concepts of the formerly existing liquid-fire or molten state of the planet that have been or are being propounded have been introduced into science in connection with theological, philosophical or cosmogonic conceptions of the world that are alien to science and are not supported by the scientific facts now known. All these conceptions must now be rejected when considering the interior of the Earth."

For almost 40 years Vernadsky fought against the concept of the white-hot origin of the Earth and in favour of the acceptance of the radioactive origin of the heat in the interior of the Earth today. His struggle was unsuccessful because his views ran contrary to cosmogonic hypotheses that dominated science. Only after the refutation of the Jeans hypothesis did Vernadsky's views find acceptance.

We hope that the theory of the origin of planets developed in the preceding lectures will be of value for the further development of geophysics and geotectonics on the lines indicated by Bredikhin and Vernadsky.

What has the new cosmogonic theory to say with regard to the thermal history of the Earth? An absolutely black body at the Earth's distance from the Sun would, as a result of balance between the absorption of solar heat and its reradiation into space, have a temperature about 277° K., or about 4°C. Meteorites apparently come to us at about this temperature. The very process of the formation of the Earth, however, must inevitably have led to some degree of heating in the material from which it was formed. When particles and larger bodies fell on to the embryonic Earth part of their kinetic energy was converted into heat. This heat energy was generated on the surface of the forming planet and was quickly radiated into space. It could not, therefore, have led to the heating or melting of the Earth. The authors of some computations have come to opposite conclusions but they used a quite incorrect law of the increase of mass with time, ignoring the continuous exhaustion of material from the protoplanetary cloud from which the planets were formed. The inevitable compression of the interior, owing to the gradual increase in the volume of the Earth, was also a source of heating. The processes have been studied by Safronov and Lyubimova, who showed that the original heating of matter in the interior of the Earth did not exceed a few hundred degrees.

The deciding factor in the thermal history of the Earth is the radioactive disintegration of uranium, actino-uranium, thorium and potassium. It must not be forgotten that several thousand million years ago there were considerably more radioactive substances in the Earth than there are today (especially potassium and actino-uranium) as a large part of them has already disintegrated.

The Earth is a poor heat conductor and the flow of heat from the interior to the surface is extremely slow. As soon as the Earth had grown big enough the heat generated by radioactive disintegration began to accumulate inside it. The process of heating the Earth by the radioactive generation of heat lasted thousands of millions of years and in the innermost part may, as calculations show, still continue.

A correct picture of the thermal history of the Earth is of great importance to geophysics and geology. It is not only important to know the temperature of the interior of the Earth at various stages of development but also the distribution of the temperature along the radius. The gravitational differentiation of matter, for example, is only possible above the specific temperature level (different at different depths) that provides sufficient plasticity of the medium.

A. P. Sokolov, in 1922, was one of the first to study the thermal history of the Earth with attention paid to the reduction in the quantity of radioactive elements due to their decay. In 1937 A. N. Tikhonov published very important papers on the mathematical study of the thermal history taking into account the internal sources of heat and radiation from the surface. A number of papers on this subject have appeared abroad during recent years.

Between 1951 and 1955, in the Geophysical Institute of the Academy of Sciences of the U.S.S.R., E. A. Lyubimova computed by strict mathematical methods the heat regime of the Earth as a whole, taking into consideration its properties and stratification. She studied a somewhat simplified model, but one that partially reflected the real Earth as it is heated and is stratified in the process of heating. The age of the Earth was taken as being 5,000 million years. To simplify the problem it was assumed that in the first 2,000 million years radioactive substances were evenly distributed, then came the instantaneous formation of the crust accompanied by the transfer of part of the radioactive substances to the outer layers. A study of this model of the Earth showed that the temperature gradient near the surface reached its maximum between 2,000 and 3,000 million years ago, after which it dropped gradually. The maximum value obtained was from 2 to 3 times the present value. From this it follows that the temperature in the Earth's crust could have been somewhat higher than it is today, which agrees with the suggestion that tectonic activity in the Earth was greater in the past than today.

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I shall now deal with the chemical composition of the Earth.

Older cosmogonic hypotheses assumed that the Earth and the planets were formed from heated gas condensations in some way or another parted from the Sun, which led them to the conclusion that originally the planets all had the same composition. The actual differences in the composition of the planets and the division of the planets into two groups were explained by the difference in mass. It was explained that the massive giant planets, with their huge force of gravity on the surface, were able to retain light gases and prevent their dissipation. The small planets of the terrestrial group whose surface gravity is much weaker, and that were supposed to be in a molten state, could not retain light and volatile atoms, especially those of hydrogen and helium, so that these elements could not be retained in their composition. As we have already said, there are facts now known that contradict this point of view (for example, the methane atmosphere of Titan, Saturn's satellite); it has also been established that its theoretical basis is erroneous (Shklovsky's research).

In Lecture 2 we explained the division of the planets into two groups. It was shown that in the parts of the cloud nearer to the Sun only particles of stony matter with a high melting point could exist, so that the planets of the inner group, including the Earth, consist mainly of silicates and metals. It is, however, important to stress that bodies from the outer regions containing ice particles of lighter materials occasionally entered the regions closer to the Sun.

Until today we have no precise data on the composition of the Earth. It is known that the Earth consists of several envelopes of various thicknesses—the crust, the intermediate mantle of silicates and the dense core, usually considered to be iron. The mass of the core is about one third of the total mass of the Earth. It was, therefore, assumed that one third of the Earth consists of nickelous iron.

During recent years a new solution of the problem of Earth's core has been suggested. It appears that the great density is to be explained merely by pressure and not by a concentration of iron. As early as 1939 V. N. Lodochnikov expressed the view that the mantle and the core differ only in their physical state and not in their composition. In 1948 Ramsey elaborated the idea that the outer electron envelopes of atoms, under a certain pressure, are, so to say, crushed and the atoms are packed more tightly together; the outer electrons in such cases acquire mobility similar to that of the electrons of metals so that non-metallic substances pass into a "metallic phase." After Ramsey's paper the existence of the core was explained by the phase transition of silicates into a metallic state due to high pressure. The sharply defined boundary of the core, perceptible through the passage of seismic waves, shows, in my opinion, that some process that begins to act at a certain critical pressure is operating there (gradual differentiation would not produce such a sharp-cut boundary). Such a process is quite probable but it would be incorrect to draw from this the conclusion that the average chemical composition of the core does not differ from the composition of the rest of the Earth. The gradual differentiation of the mantle could, of course, lead to a certain concentration of iron in the core.

The Lodochnikov-Ramsey idea may be supported by a comparison of the composition of the terrestrial planets and the Moon, all of which were formed in the same zone of the circumsolar cloud. As we know, the average densities of these bodies differ very considerably. The Moon and Mars, for example, have a lower average density than the Earth. In place of the old, rather fantastic, explanation of this phenomenon—the difference in the atomic composition of the planets—a number of researches have been published showing that the difference in mean density may be entirely due to differences in pressure, i.e., in the extent to which the inner layers, having the same chemical content, are compressed. This viewpoint is shared in the latest papers of a number of scientists. As the planets differ in mass the pressure in their central parts will also differ so that the compressed part of the whole mass will be greater or less. The computations of the internal constitution of the terrestrial planets and the Moon made by Ramsay, Bullen and Kozlovskaya, on the assumption that the composition of the mantle and core of the Earth are, in the main, alike, showed that all these bodies, with the exception of Mercury, have the same composition.

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Our satellite, the Moon, is naturally of interest to geologists as well as astronomers. We cannot ignore the fact that some authors of manuals of astronomy and geology, as well as authors of popular outlines, still continue to support Darwin's theory of the Moon's origin although it has long since been refuted. According to Darwin the Moon was separated from the Earth. It was assumed that the Earth once rotated at a much greater velocity than now. If the period of its free oscillation coincided with a half-period of its rotation, the tidal wave caused by the Sun could, said Darwin, be of such magnitude on account of the resonance, that a considerable part of the Earth would be separated and form a satellite, the Moon. This hypothesis was propounded at the end of the last century and became most popular when Jeffreys in his book *The Earth* (2nd Edition, 1929) supported it with mathematical calculations and geophysical considerations. A year later Jeffreys published a more detailed calculation that fully refuted the hypothesis. It was shown that the tidal wave would be damped by friction and could not lead to partition. This research was most convincing and was never disputed.

A few words about the character of the Moon's surface. The well-known Wegener theory explained the lunar craters as being due to the fall of meteorites by analogy with the famous meteorite crater in Arizona. Similar, but smaller craters are to be found in the U.S.S.R. on the Island of Saarema. As there is practically no atmosphere on the Moon such craters should be preserved for a long time. There is, however, no reason why all lunar craters should be attributed to the fall of meteorites. As the Earth and the Moon are of similar composition (radioactive substances included) the depths of the Moon should also be heated with the resultant volcanoes, lava streams and crater formations.

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The meteorites in our collection are not indicative of the average composition of solid particles in the entire solar system because that composition depends on distance from the Sun. Meteoric bodies may be different in composition and to a greater or lesser degree similar either to comets (or rather to the nuclei of comets) or to asteroids. As B. Y. Levin pointed out, the meteorites do not show precisely the chemical composition of even those meteoric bodies that move within the region of the Earth's orbit; friable bodies would disintegrate in the atmosphere and would not reach the surface of the Earth. Nevertheless the study of meteorites provides many valuable data.

We may now say that it has been fully established that the Earth and the meteorites are of similar composition; I emphasize that I speak in terms of their atomic and not their mineral composition. The present-day surface of the Earth does not contain primary matter but igneous rocks and the sedimentary deposits that come from them by erosion and weathering. On the surface, therefore, we have the results of the further evolution of the Earth. For this reason meteorites may differ in some way or another mineralogically from the minerals of the Earth. The atomic composition of the whole Earth and of the meteorites is, in general, the same. This is only one of the particular cases, a particular manifestation of the common composition of matter in the universe, a fact that is year by year becoming more certain as it is confirmed by observational data. In particular, observations point, on the one hand, to the similar composition of the planets and the Sun (as far as the heavy elements are concerned) and, on the other hand, to the similarity in composition of the Sun and the other stars. The development of spectroscopic research gives us still more evidence of this unity of matter in the universe. As far as the Earth and the meteorites are concerned this similarity does not include the lighter elements, such as hydrogen and helium, which are abundant in the Sun and deficient on Earth, since they could not reach the latter in any great quantities and be retained there.

Different, often contradictory, conclusions have been drawn from this similarity in the composition of the Sun, the Earth and the meteorites. There are some people who regard this as proof that the Earth was separated from the Sun. At the same time the similarity of composition between the Earth and the meteorites is just as good an argument for a connection between them and not with the Sun. Many mineralogists who have studied the composition of meteorites explain the similarity of their composition with that of the Earth by ascribing their origin to a disintegration or explosion of a formerly existing planet similar to the Earth. This argument works just as well in reverse—the Earth is composed of meteorites.

Champions of the explosion hypothesis laid particular stress on the division of meteorites into stone and iron bodies which would correspond to the stone mantle of a planet and its iron core. As we have seen, however, belief in the iron core of the Earth has been shaken. At the same time no probable causes leading to the explosion of a formerly existing parent planet have ever been proposed. We know quite a lot about the forces acting within the Earth but amongst them there is none that threatens to blow up the planet. The explosion hypothesis is an artificial construction not founded on the proved laws of nature. We criticized this hypothesis when we spoke of the origin of the asteroids. Personally I think it highly improbable that planets should ever have exploded or disintegrated but the collision and splintering of asteroids undoubtedly occurred many times as did also their re-formation from smaller particles. The structure of meteorites, which includes different particles, from chondri up to the biggest fragments, tells us that they have passed through a lengthy and intricate development during which the processes of association and dissociation alternated on numerous occasions.

Meteorites result from the collision and splintering of asteroids, i.e., bodies formed in the same zone as the terrestrial planets. This explains the similarity of their composition and that of the Earth.

We have noted that the chemical composition of the Earth and the meteorites is similar to that of the Sun and interstellar material (with the exception of light elements). There are also some differences that are explained naturally by the cosmogonic theory; namely, by the fact that the Earth was formed from solid matter and, therefore, consists mainly of those substances, of those chemical elements, that could enter into the composition of particles at temperatures existing in the terrestrial zone of the circumsolar cloud. Oxygen, for example, forms more than a quarter of the Earth's mass. As it is chemically active it easily forms compounds, oxides of the silicates and metals that constitute the basis of rocky substances. At the same time chemically inert nitrogen is present in the Earth only in small quantities.

The inert gases are almost absent in the Earth's atmosphere—there is little neon (abundant in interstellar material) and little, even, of such heavy gases as crypton and xenon—being inert they naturally do not enter into compounds. Argon, which is extremely rare in interstellar material is, however, abundant on Earth. This is because it is a product of the decay of a radioactive isotope of potassium, K^{40}. The rapid decay of K^{40} as well as evidence of its abundance on Earth explain the presence of large quantities of the gas in the Earth's atmosphere.

We shall now discuss briefly the formation of the seas and the atmosphere which is also part of the problem of the Earth's origin and evolution.

We have shown that the Earth was built up mainly from particles with a high melting point and bodies formed from them. Further research should show precisely whether the temperature conditions in the Earth zone of the circumsolar cloud were such that a sufficient quantity of water vapour could freeze on to or be sorbed by the particles or whether the water was brought by icy bodies flying into the Earth zone from distant regions, and containing volatile substances in condensed form. On Earth they naturally melted and evaporated, if they remained on the surface, but would be partly retained if they were quickly covered by the next layer of particles. In this way the Earth had water on its surface and an atmosphere from the very beginning. In the depths of the Earth there were also some water, methane and other substances which were later squeezed to the surface and came up through cracks, on their way often going through a number of chemical processes of synthesis and separation. These conclusions of ours that water and atmosphere existed from the very beginning may be of interest to geochemists and mineralogists.

More recently geophysicists and geochemists have come to the conclusion that the Earth's atmosphere is of secondary origin. From our point of view this is undoubtedly so—the atmospheres of all the planets nearer the Sun were formed as a result of the long-term escape of gas from their interiors. This process still continues. The present composition of the Earth's atmosphere is, as Vernadsky has shown, to a considerable extent due to the activities of living organisms.

We must say a few words about the origin of life on Earth, in connection with Oparin's theory. It will be remembered that this theory contains the following statement: living matter arose out of such simple organic compounds as methane and formaldehyde, present in solution in the waters of the ocean, by means of the gradual complication of their composition.

How did methane and other compounds find their way to the Earth's surface and into aqueous solutions? This is a question for cosmogony.

Oparin was compelled to take into consideration the most widespread cosmogonic view of the time, the view that the Earth first consisted of hot gas which then turned liquid as it cooled and out of which the solid phase gradually formed. In his search for ways in which methane might appear Oparin examined the following sequence: when the cooling took place carbides (compounds of carbon and the metals) were formed. Water vapour, also formed during the cooling, came into contact with the carbides at high temperatures, and the reaction (shown by Mendeleyev) produced methane. Methane rose, together with vapour, through cracks in the cooling surface of the Earth and thus appeared in an aqueous solution.

It must be stressed that Oparin needed the high temperature solely for the formation of methane, the further process leading to the appearance of life took place in water, i. e., at temperatures not higher than 100°C.

As we have said above, methane, carbonic acid, ammonia and cyanogen existed on Earth from the very beginning and at the earliest stage were to be found on Earth's surface in aqueous solutions. There is, therefore, no need for any special conditions for the formation of methane—it existed already. The shallow basins of the young Earth were warmed by the Sun which could provide a high enough temperature in some of them for life to be born on Earth.

The conclusions to be drawn from our cosmogonic theory, therefore, show that conditions existed on Earth, from the very beginning, such as were necessary for life to appear.

* * *

The stratification of the Earth into several envelopes of varying density is a fact of great importance for geophysics.

Earlier geophysical conceptions, based on the original molten state of the Earth, stated that the stratification of matter by density took place in the early stages of the Earth's existence. According to this point of view the main redistribution of matter inside the Earth was completed before the planet's geological history began and that since then only secondary processes have taken place.

According to our cosmogonic theory, the bodies from which the Earth was formed were of different sizes—from dust particles up to bodies of asteroidal size—and had developed in different ways. The Earth formed from such material, could not be uniform throughout. Different parts of the interior of the Earth differed in their physical properties, in the details of their chemical composition, in the concentration of radioactive substances, etc. The assertions that we meet with in geological literature that our theory postulates a uniform structure for the primordial Earth that is changed only by pressure, are true only if huge volumes are considered. Deviations from uniformity that occurred in the past have been preserved in varying degrees up to the present day.

For some time the original distribution of substances was retained in the Earth, including some big local cases of heterogeneity. It was only after the Earth became sufficiently plastic as a result of heating processes that gravitational differentiation began, the sinking of huge heavy regions and the rise of the lighter. These displacements began several thousand million years ago, they still continue today and are far from being finished.

At the early stages of theory we explained the formation of the iron core of the Earth by gravitational differentiation. The viscosity of the interior of the Earth, despite its heated condition, is so great that, as E. N. Lyustikh has shown, this process took place at an extremely slow rate so that during the past thousands of millions of years there could have been only a small concentration of heavy substances (but not heavy elements) in the central parts of the Earth. A comparative analysis of the internal constitution and composition of the terrestrial planets and the Moon has been carried out by Kozlovskaya; she also showed that gravitational differentiation has made very insignificant progress.

The Earth's crust was formerly regarded as a slag layer that came to the surface during the original stratification of the Earth. The solidification of the crust was the end of the molten, fiery stage.

From the standpoint of our theory, the upper layer of the Earth, the layer that is available for direct observation, came into being during the radioactive heating of the interior, the lighter, less viscous molten substances having floated or been squeezed to the surface. It must be borne in mind that the process of the formation of the crust could have been different in different parts of the globe.

Thus we see that the process of the formation of the Earth's crust is not due to the rapid cooling of the surface but to the lengthy interaction of the external and interior zones of the Earth that, apparently, continues to the present day.

Without touching on other problems connected with stratification—that is the business of the geochemists—I want to say a few words about the distribution of radioactive substances. The difficulty that arose shortly after the physics and chemistry of radioactive substances were applied to the Earth is well enough known. If we assume that the radioactive content throughout the interior of the Earth is the same as, say, that of granite, then there would be a greater heat flow than is observed on the surface. It was, therefore, thought that radioactive substances were in some way concentrated in the crust, and even in a very thin layer.

We must say that we differ from some investigators in that we never believed that radioactive substances were all concentrated in the upper layers of the Earth. There is undoubtedly a higher concentration in the Earth's crust, but a considerable part of the radioactive substances may remain in the depths of the Earth. This point of view is now held by many scientists.

The displacements that we spoke of in connection with the gravitational differentiation of the Earth did not always take place smoothly, most frequently they were sudden shifts during which accumulated stress was discharged. This process also continues in our days. Is not this process the cause of deep-focus earthquakes? I must limit myself to posing the question.

The intensity of tectonic and geological processes is to a great extent dependent both on the temperature itself and on its gradient. Lyubimova's calculation, showing that the heating of the Earth near its surface has already most likely passed the maximum, may mean that the total intensity of processes in the Earth's crust was at one time (possibly in the Archean) higher than now and has, in general, been gradually decreasing since then. Does this not explain the presence of extensive mobile zones (geosynclines) in the distant past and their gradual replacement by less mobile geological platforms? This offers certain new possibilities for the development of geotectonic theories.

The main problem in geotectonics is, of course, the causes that led to the formation of mountains. There are many books on this subject and numerous hypotheses have been propounded. The most widespread until recently was the contraction hypothesis that explained the formation of mountains by the contraction of the Earth's crust as a result of the cooling of the globe. Numerous contradictions and faults were gradually exposed in the hypothesis but its main fault (and also of other existing hypotheses) is the absence of a properly elaborated physical theory of contraction and its results and the absence of a quantitative appreciation of the possible effects of the postulated causes. Academician L. S. Leibenson subjected the problem to a quantitative analysis using the methods of the theory of elasticity and came to the conclusion that the contraction of the crust, if it occurred at all, could produce only small folds about a metre high and nothing more.

When the role of radioactivity in the Earth was understood it became difficult to retain the old views on the cooling of an originally hot Earth. There are still attempts, however, being made to explain tectonic movements by contraction and cooling, caused by the decrease of radioactivity as time goes on. Two quite different concepts are confused here: the decrease in heat generation and the decrease of temperature. There is no doubt that radioactive substances are gradually becoming exhausted so that the amount of heat generated in each succeeding thousand million years is less, but this does not mean that the temperature in the interior of the Earth decreases. On account of the low heat conductivity of the Earth only a small part of the accumulated heat finds its way out, so that even small regular additions of heat continue to raise the temperature. Equilibrium will be established only at a later stage and then the slow decrease in temperature will begin. Consequently, the new variants of the contraction hypothesis also lack a physical basis, i.e., the necessary cooling effect.

In recent decades a number of different pulsation hypotheses have been put forward together with the contraction hypothesis. Instead of the one-sided development, contraction, the pulsation hypothesis admits alternate contraction and expansion. The physical character of the motive forces and the causes of the changes have not been explained. There have been attempts to connect the concept of an originally cold Earth with the contraction hypothesis, giving the gradual increase in the density of the Earth as the cause of contraction instead of the cooling of a once hot globe. I am not the one to judge the geological aspect of these researches but they prove that a change in cosmogonic ideas opens the way for creative thinking in the field of geology.

The rapprochement between cosmogony and the sciences studying the Earth is something that has already begun and will, no doubt, continue.

* * *

In these lectures on the theory of the origin of planets we have established the state of the material as it was before the process of planet formation began. It has been shown that the protoplanetary material could only have been a dust and gas cloud rotating about the Sun. The evolution of that cloud led to the formation of a swarm of bodies of asteroidal size and smaller particles moving in various elliptical orbits. On the basis of this state of the protoplanetary material and the laws of nature we explained the basic properties of the solar system. Examining the connection between the Sun and the Galaxy we expounded a hypothesis of the origin of the gas-dust protoplanetary cloud through its capture by the Sun from galactic material. We gave a theoretical basis for the capture and its probability. Lastly, we saw that the new cosmogonic theory does not contradict geophysical, geochemical and geological evidence and may provide those sciences with valuable material with which substantiate their ideas. The extensive and profound development of the theory proved its viability and gives us reason to believe that we are on the right path, that the theory reflects a substantial part of objective reality. I do not think that the theory is complete. It must and will be further developed, enriched with new content and, when necessary, will change. As the theory is a regular link in the chain of scientific development, the greater the extent to which it becomes the common property of a large community of scientists, the quicker will it achieve its objective.

We shall investigate a case of formula (6) (see page 56) when the right member $\leqslant 0$, i.e.,

$$\frac{k^2 M}{2}\int_{R_1}^{R_2}\frac{\varphi(\rho)\,d\rho}{\rho}-\frac{k^2 Mm}{2R}\leqslant 0$$

from which we get

$$R\leqslant\frac{m}{\int\frac{\varphi(\rho)\,d\rho}{\rho}}$$

Substituting this into formula (7), we get: The rotational momentum of the planet $\geqslant k\sqrt{M}\int\sqrt{\rho}\,\varphi(\rho)\,d\rho-$

$$\frac{k\sqrt{M}\cdot m^{3/2}}{\sqrt{\int\frac{\varphi(\rho)\,d\rho}{\rho}}}$$

With the value of $m=\int_{R_1}^{R_2}\varphi(\rho)\,d\rho$, we get:

$$\frac{1}{k\sqrt{M}}\ (\text{rot. momentum})\geqslant\int\sqrt{\rho}\,\varphi(\rho)\,d\rho-\frac{\left[\int\varphi(\rho)d\rho\right]^{3/2}}{\sqrt{\int\frac{\varphi(\rho)\,d\rho}{\rho}}}\cdot\qquad\text{(A)}$$

The limits of the integration are always the same, i.e., R_1 and R_2. We shall prove that the right member of (A) is *always positive* whatever the distribution function $\varphi(\rho)$. The sign is the same as the sign of the difference of the squares of two members of (A), i.e., the sign of the expression:

$$\int\frac{\varphi(\rho)\,d\rho}{\rho}\cdot\left[\int\sqrt{\rho}\,\varphi(\rho)\,d\rho\right]^2-\left[\int\varphi(\rho)\,d\rho\right]^3.\qquad\text{(B)}$$

We now introduce the independent variable $x = \sqrt{\rho}$, so that $d\rho = 2\,x dx$ and designate $\varphi(\rho) = y(x)$. Then (B) becomes the following (after being divided by 8):

$$\left[\int yx^2\,dx\right]^2 \cdot \int \frac{ydx}{x} - \left[\int yx\,dx\right]^3$$

with positive integration limits α and β and positive values for $y(x)$.

We substitute the integrals by sums, dividing them into equal intervals Δx, assuming that the function $y(x)$ is to be integrated in this way (the only restriction). Then, dropping the factor $(\Delta x)^3$ we get:

$$\left[\sum_i y_i\,x_i^2\right]^2 \cdot \sum \frac{y_i}{x_i} - \left[\sum y_i\,x_i\right]^3 \qquad \text{(C)}$$

After removing the brackets in (C) the members containing y_i^3 disappear and there will be two types of members left:

$$y_i^2\,y_k\left(\frac{x_i^4}{x_k} + 2x_i\,x_k^2 - 3x_i^2\,x_k\right),$$

$$y_i\,y_k\,y_l\left(2\,\frac{x_i^2\,x_k^2}{x_l} + 2\,\frac{x_i^2\,x_l^2}{x_k} + 2\,\frac{x_k^2\,x_l^2}{x_i} - 6x_i x_k x_l\right).$$

We can show that in both expressions the coefficients are positive.

In the first expression this is obvious since the coefficient is identical to

$$\frac{x_i}{x_k}\,(x_i - x_k)^2\,(x_i + 2\,x_k).$$

Let us take the second coefficient which is equal to

$$\frac{6}{x_i\,x_k\,x_l}\left(\frac{x_i^3\,x_k^3 + x_i^3\,x_l^3 + x_k^3\,x_l^3}{3} - x_i^2\,x_k^2\,x_l^2\right).$$

In brackets we have the difference between the arithmetic and geometric means of three positive numbers $x_i^3 x_k^3$, $x_i^3 x_l^3$, $x_k^3 x_l^3$, i.e., the value is always positive.

Thus we have shown that the expression (C) and, therefore, (B) and the right-hand part of (A) are always positive for any distribution function $\varphi(\rho)$. It follows that, under the conditions assumed, the rotational angular momentum of the planets is always positive and has the same mathematical sign as the angular momentum of orbital revolution, i.e., *the rotation of the planets should be direct.*

In making our calculations the astronomical unit was used as the unit of distance and the year, divided by 2π, as the unit of time. We examined the motion of three bodies of equal mass and equal to that of the Sun (the latter taken as unity) moving in one place. Under these conditions the constant of gravitation is equal to 1, which simplifies the calculation. Movement was studied in respect of one of the bodies with which we connected the reference point of the system of coordinates (point O). The equations of the relative motion of the bodies with coordinates of x_1, y_1, and x_2, y_2 are the following.

$$x_1'' = \frac{-2x_1}{r_{10}^3} - \frac{x_1}{r_{12}^3} + \frac{x_2}{r_{12}^3} - \frac{x_2}{r_{20}^3},$$

$$y_1'' = -\frac{2y_1}{r_{10}^3} - \frac{y_1}{r_{12}^3} + \frac{y_2}{r_{12}^3} - \frac{y_2}{r_{20}^3}$$

with a similar pair of equations for x'' and y''_2. Here r_{ik} = the distance between the bodies P_i and P^k.

Precise and detailed computations were made at the Geophysical Institute of the Academy of Sciences of the U.S.S.R. under the direction of N. N. Pariisky. The initial position and velocities of the bodies P_1 and P_2 and the positions and velocities for the extreme time limits are given in the table:

t	x_1	x'_1	y_1	y'_1	x_2	x'_2	y_2	y'_2
8000	141.10	0.07172	169.81	—0.01627	321.49	0.05388	—8490.59	—0.9327
0	291.50	—0.01950	— 49.958	—0.05608	320.00	0.000	—1200.000	—0.9549
—129764	17004	—0.1283	10975	—0.0843	—28636	0.2261	116430	—0.9053

G. F. Hilmy studied the problem from the strictly classical standpoint, so that we must give an exact definition of capture. Let P_0, P_1, and P_2 be three points attracting one another according to Newton's law; let r_{ik} be the distance between them. Let ρ be the distance between P_2 and the centre of gravity of points P_0 and P_1.

We shall consider capture to have taken place between the bodies P_0 and P_1 if

$$r_{10} \rightarrow \infty \text{ with } t \rightarrow -\infty \quad (t = \text{time})$$

and if a moment of time T^* and a positive number R can be found that will give $0 < r_{10} < R$ for all $t > T^*$.

This, of course, is the same as the definition in Lecture 3, except that it is expressed in a form indispensible for mathematical analysis.

The following symbols will now be employed:

$$r = \min (r_{10}, r_{12}, r_{20}),\ r' = \min \left\{ \frac{dr_{10}}{dt}, \frac{dr_{12}}{dt}, \frac{dr_{20}}{dt} \right\}.$$

Hilmy's first result was the following. If, at a certain moment t_1

$$r(t_1) > 0, r'(t_1) < -\sqrt{\frac{8M^*}{r(t_1)}}$$

(where M^* is a constant dependent on the masses of the material points), then all three distances r_{10}, r_{12}, r_{20} increase infinitely when $t \rightarrow -\infty$.

What does this result tell us? It is the criterion—no two of the three bodies being studied, at any time in the past up to t_1, formed a system by means of capture, so that in this sense their motion had been independent.

Hilmy's second result is formulated as follows. If the energy constant = $H>0$, and if two positive numbers R and $\varepsilon > R$ and a moment of time t_2 can be shown so that

$$r_{10}(t_2) < R, \ \rho(t_2) > 2R, \ \rho'(t_2) > 0,$$

$$\rho'^2(t_2) - \frac{16M}{\rho(t_2)} > \frac{2}{\mu} H + \frac{2m(m_0 + m_1)}{\mu(R-\varepsilon)}$$

(where m, μ and M are constants depending on mass) then for all $t>t_2$ the point P_2 moves steadily into infinity from the centre of gravity of points P_0 and P_1, and the distance between P_0 and P_1 remains no greater than R. From the standpoint of the theory of capture this result has the following meaning: if the capture occurred before the moment t_2 it will not be disrupted at any later time.

At the ends of the parts of the orbits computed in the example I have given, Hilmy's criteria are satisfied. This means that with the initial conditions I give, the capture is effected when the motion is studied in a period ranging from $-\infty$ to $+\infty$. This is a solution of the problem of the possibility of capture in the sense of the strictly classical definition of that phenomenon in celestial mechanics.

And now, here is Hilmy's principal theorem which I reproduce word for word in his own formulation: "The measure of the set Ω of those points in the phase space of the system of three bodies that denote the initial states of the system of three bodies leading to capture, cannot be equal to zero."

G. F. Hilmy produced a very fine method of proof based on the qualitative theory of differential equations, but his proof depends on the existence of one solution: in other words it depends on the example I have found.

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