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CONGRES GEOLOGIQUE INTERNATIONAL

twenty-fourth session
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CANADA-1972

SECTION 15

Planetology

Planétologie

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CONVENERS / ORGANISATEURS
P. M. Millman; M. R. Dence

MONTREAL, 1972

PREFACE

This Planetology Symposium is designed to present an interdisciplinary survey of the current knowledge concerning the physical structure and the surface features of the solid planetary bodies in the solar system, ranging in size from the earth down to the smaller asteroids and satellites. In the case of the earth itself only those surface features presumed to be of space-impact origin are included.

Planetology is a fast-moving field of research. Hence, most of the material included in this volume serves as background information to the oral presentations of the speakers. It should also be noted that the Symposium includes additional invited speakers whose names do not appear here.

Our thanks go to all those who were able to prepare abstracts and papers so far in advance of the Congress. Thanks should also be expressed for the assistance rendered by the members of the Symposium Organizing Committee, and to D. P. Gold, Ian Halliday, P. B. Robertson and R. W. Tanner, who assisted in the review of papers and abstracts.

Finally, we should like to pay tribute to the memory of our co-worker, Dr. J. A. V. Douglas, whose untimely death on June 18, 1971, cut short his active career in meteoritics and his efficient contribution as the original secretary of our Organizing Committee.

The Conveners:

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The Planetology Symposium was co-sponsored by:

The International Astronomical Union

The Meteoritical Society

The International Association of Geochemistry and Cosmochemistry

The International Association of Planetology

Organizing Committee:

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PRÉFACE

Ce colloque de planétologie est conçu pour présenter un aperçu interdisciplinaire des connaissances acquises sur la structure physique et les caractéristiques de surface des corps planétaires solides du système solaire, dont la dimension s'étend de la terre aux plus petits astéroïdes et satellites. Dans le cas de la terre-même, seuls les principaux traits de surface qu'on croit être causés par la collision de corps dans l'espace seront examinés.

La planétologie est un champ de recherches qui s'étend rapidement. C'est pourquoi les données contenues dans ce volume sont destinées à servir de toile de fond aux communications orales des conférenciers. Il faut aussi remarquer que d'autres conférenciers dont les noms n'apparaissent pas ici ont été invités à ce colloque.

Nous tenons à remercier tous ceux qui ont réussi à rédiger leurs résumés et communications à une date qui précède de beaucoup l'ouverture du Congrès. Nous remercions aussi les membres du comité d'organisation du colloque qui nous ont apporté leur aide, de même que messieurs D. P. Gold, Ian Halliday, P. B. Robertson et R. W. Tanner qui nous ont aidés dans la révision des communications et résumés.

Enfin, nous voudrions rendre hommage à la mémoire de notre collègue, Dr. J. A. V. Douglas, dont le décès subit, le 18 juin 1971, a mis fin abruptement à une carrière active consacrée à l'étude des météorites. Sa contribution efficace en tant que premier secrétaire de notre comité d'organisation a été hautement appréciée.

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Ce colloque de planétologie fut organisé avec la collaboration de:

L'Union internationale de l'Astronomie
La Société météoritique
L'Association internationale de la Géochimie et Cosmochimie
L'Association internationale de la Planétologie

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Origin and Early Development of the Planets

Origine et Développement Primaire des Planètes

Origin and Early Development of the Planets

A. G. W. CAMERON,
U.S.A.

ABSTRACT

Extensive numerical calculations have been carried out to determine the structure of the primitive solar nebula. The resulting structure shows a dominance of the radial pressure gradient near the center, and a dominance of the centrifugal forces throughout most of the outer region. Thermal convection and Eddington-Sweet circulation currents can be expected to cause a rapid dissipation of the disk, requiring only a few centuries. It is therefore postulated that the planets were formed in an exceedingly hot initial state due to their rapid rates of accumulation. Beyond one or two astronomical units from the center, the original interstellar grains should not be completely destroyed during the formation of the disk, and these will form the nuclei for subsequent chemical condensations and chemical accumulation. Inside this distance, nucleation of condensed materials must occur within the nebular gases. The moon may have been formed from an extended silicate atmosphere of the initial earth, if much of the final mass of the earth was formed by a collision of two bodies of not too incomparable mass. The nebular gases will have been removed through the operation of the T Tauri phase solar wind, which is also likely to have removed primitive planetary atmospheres. Secondary planetary atmospheres and the more volatile elements are expected to be incorporated in the terrestrial planets as smaller, colder bodies are subsequently swept up in the vicinity of the planetary orbits.

THIS PAPER summarizes many of the conclusions reached by the author during the last four years in a quantitative investigation of the structure and evolution of the primitive solar nebula (Cameron, 1970, 1971). Models are constructed using physical principles similar to those used by astrophysicists in constructing numerical models of a galaxy or of a star. A model consists of gas in a quasi-static situation, subject to some kind of force balance. The forces include the gravitational force which is the negative derivative of the gravitational potential, the pressure gradient force, and centrifugal force due to rotation. The boundary conditions which such a model must satisfy are basically derived from the astrophysics of star formation. The observable consequences can in principle be checked through current investigations of the early history of the solar system, which involves investigations of meteorites and planetary bodies within our solar system.

It would be out of place in the Proceedings of a Geological Congress to devote much space to a discussion of the astrophysics of star formation. It appears that stars form when clouds of interstellar gas become unstable against collapse and fragmentation, and undergo compression from densities of a few atoms per cubic centimeter toward densities which are more characteristic of normal stellar interiors.

The models which have been calculated represent very crude approximations to an expected fragment of an interstellar cloud. The initial fragment is repre-

Authors' addresses are given at the back of this book.

sented by a spherical distribution of matter, with uniform rotation, but not necessarily with a uniform density distribution in the interior. The density has been uniform in some cases, and has been taken to vary linearly between a central value and zero at the surface in other cases. The results due to either of these distributions appear to be quite similar. The fragments have been given an angular momentum corresponding to a rotation rate such that the original interstellar cloud would corotate with its motion around the center of the galaxy, and conserve local angular momentum during the collapse. In calculations done with Mr. Milton Pine, one of my graduate students, the fragment has been taken to contain two solar masses, and after the sphere is allowed to flatten into a thin disk, the radius of this disk is several tens of astronomical units. This seems a reasonable model to represent conditions in the solar system. Mass will be lost from the sun during the so-called T Tauri phase, while it is contracting toward the main sequence, amounting probably to several tens of per cent, and further mass will be lost from the primitive nebula when the T Tauri phase solar wind turns on and sweeps the nebula gases away. Mathematical details utilized in the model construction have been indicated elsewhere and will not be repeated here. Instead, I shall concentrate on a discussion of the types of physical conditions found in the disk, and the probable consequences for the early history of the solar system.

In our approximate model of this primitive solar nebula, we have concluded that near the center the gas pressure in the central plane of the disk is of order one millibar, and the temperature is somewhat in excess of 2000°K. The total amount of material in a column of one square centimeter cross section perpendicular to the plane of the disk is somewhat more than 10^5 grams per square centimeter. The thickness of the disk is of the order of magnitude of a half of an astronomical unit near the central regions. These are the conditions immediately after the formation of the disk as a result of the collapse of the interstellar gas, and no estimates have yet been made of the rate at which this condition will change as the disk evolves.

At around one astronomical unit from the centre, the conditions will not be greatly different from those at the center. The surface density of the disk is reduced by a moderate factor, the temperature is reduced to about 1500°K and the thickness of the disk is slightly greater than that of the center. At five astronomical units, where we might expect Jupiter to form, the surface density of the disk is an order of magnitude less than that of the center, the temperature only 600° to 700°K, and the thickness nearly one astronomical unit. Out at 20 astronomical units, where conditions which give rise to the planets Uranus and Neptune, and possibly also to the comets, can be expected to exist, the surface density is nearly two orders of magnitude less than that near the axis of the disk, the temperature is less than 200°K and the thickness is slightly greater than one astronomical unit. These are very general conditions which would probably not be greatly altered if we had made moderately different assumptions about the way in which the disk was formed.

It should be noted that the properties of the disk change relatively slowly over the central region. There is no independent body formed at the center of the disk which can be identified with the sun. Thus, the sun must form from the disk as a result of gaseous dissipation.

There are a number of powerful dissipation mechanisms, which can be expected to operate in the disk, which will bring mass toward the center of the disk and transport angular momentum outward. Near the axis of the disk, at higher surface densities, the disk will be subject to convection. This convection gives rise to a strong turbulent viscosity which provides friction between the adjacent shearing layers, which tends to make an outer layer rotate faster and an inner layer more slowly, thus transferring angular momentum away from the spin axis. There are also large-scale circulation currents which will tend to operate in the disk. These arise from the effects of radiation flow and from the fact that the forces which oppose that of gravity, the pressure gradient and the centrifugal forces, do not have the same vector directions. In a rotating star the currents which arise from the slight imbalance in these forces are called Eddington-Sweet circulation currents, and they are extremely slow. The evolution of the stars can in general be computed without attention being paid to these circulation currents. As the rotation of the star becomes more rapid, the circulation currents also speed up, and as the star becomes extremely flattened the circulation currents can be expected to become quite vigorous. In the limit of great flatness which is represented by the primitive nebula under consideration here, I expect that the circulation currents will amount to a substantial fraction of sound speed in the gas. These circulation currents will also result in a net outward transport of angular momentum, as a result of which there will be a rapid flow of matter toward the spin axis.

One of our major objectives is to evolve our model of the primitive nebula, to examine the details of the dissipation and to determine its time scale. A very crude estimate for the characteristic time scale of the dissipation near one astronomical unit is two or three centuries. This is an exceedingly short time scale, which has very important consequences for planetary formation, as is discussed below.

With such a short dissipation time, we must be very concerned with the rate at which large bodies can be accumulated within the primitive nebula. The small particles of chemically condensed material, which can be expected to be present initially in the gas, will ordinarily flow wherever the gas flows, unless the particles can accumulate into much larger bodies which are able to move with a significant degree of independence of the motion of the gas.

In this connection, it should be noted that although interstellar grains can be expected to be completely evaporated near the center of the primitive nebula, the principal constituents, iron and magnesium silicates, will not have been evaporated at radial distances greater than one or two astronomical units. This means that the original interstellar grains will remain available as condensation centers in the entire outer part of the primitive nebula for the recondensation of the more volatile elements which are evaporated from the grains as the original nebula is formed, and which become available for condensation again as the nebula cools. In the inner part of the disk, a cooling of the nebula will result in the formation of fresh condensation centers from the gas, and it is not easy to predict the size of these. The original interstellar grains are expected to have dimensions of the order of a tenth of a micron or a few tenths of a micron.

The primitive solar nebula was obviously an extremely complicated environment, and we must work patiently to evaluate and predict all of the various mechanisms which may have been operating there. Let us consider some of the processes which will affect the particle accumulation process.

For the smallest particle sizes, accumulation cannot be very rapid. The particles will run into one another partly as a result of their Brownian motion in the gas, and partly as a result of acceleration by very weak electric fields which can be expected to be produced in the nebula through the interaction of convection with ionization produced by natural radioactivity. I rather suspect that this state of accumulation may be greatly accelerated as a result of the natural magnetism of the interstellar grains. Purcell and Spitzer (1971) have recently concluded that the interstellar grains probably must be ferromagnetic or superparamagnetic so that they can be aligned by the very weak interstellar magnetic field. If this is so, and it appears consistent with evidence from meteorites (Brecher, 1971), then the interstellar grains will be able to come together to form considerably larger units, both during the late stages of the collapse that forms the primitive solar nebula and during the early history of the solar nebula itself. The cross section for magnetic capture of one particle by another will be very much greater than the geometric cross sections which would be involved in an ordinary non-magnetic collision. Until these particles become large, they will follow quite closely the motion of the gas. This may nevertheless transport them extensively within the solar nebula, owing to the large-scale circulation currents.

As the particles become larger, they can move significantly with respect to the gas. Near the center of the disk, the radial pressure gradient is comparable in value to the centrifugal force; gradually the radial pressure gradient becomes less important away from the spin axis, but even at 20 astronomical units it is a few per cent of the centrifugal force. The radial pressure gradient gives a partial support to the gas at these various distances, and hence the gas will rotate at less than the Kepler orbital velocity. However, larger particles do not receive any pressure-gradient support from the gas, and hence they will rotate at Kepler orbital velocities faster than the gas rotation. Consequently the particles will always be subject to a gas drag, which will make them spiral inward within the nebula. Superimposed upon this tendency, the gas will drag the particles in the radial direction as a result of the large-scale circulation currents. The resulting motions of the particles may be quite complicated. They also will have a component of force toward the center of the disk, which takes them across a gradient in the circulation velocities. Because the gas drag is a function of particle dimensions and mean densities, particles will move at different relative velocities with respect to the gas, thus running gently into one another. This promotes the rapid accumulation of larger bodies from the gas.

When the accumulated bodies become very much larger in size, they may start to capture material by gravitational attraction. Gravitational attraction would certainly be extremely important for a body the size of the Earth, but it can become important long before this size is reached. One might expect that primitive atmospheres will also be captured gravitationally about the larger bodies.

At 20 astronomical units and greater in the disk, the interstellar grains will retain an icy condensation. This is precisely the right sort of raw material for the formation of comets. Comets are believed to consist in large part of icy materials with a great deal of included dusty particles, which may very well be the original interstellar grains. Collisions among the comets can be expected to build up planetary bodies, and this is probably how Uranus and Neptune were formed. These two planets may in turn have been responsible for ejecting most of the comets, which did not physically collide with them, toward greater distances in the solar system, where they form a reservoir and can occasionally be perturbed once again and moved toward the inner solar system by the motion of passing stars. The interior densities and some model calculations for the planets Uranus and Neptune are consistent with the idea that about 80 per cent of the mass of these planets is cometary in basic composition, and that to this has been added about 20 per cent of the mass in the form of light gases, hydrogen and helium, probably directly captured from the primitive solar nebula.

Near five astronomical units, the icy condensates have long since evaporated, and the basic geochemical question concerns whether sulfur is retained in the original grains. At temperatures below about 680°K, the sulfur can be expected to combine with iron to form troilite, whereas above this temperature, it will combine with the hydrogen of the primitive solar nebula to form H_2S. At any rate, when the particles come together they are more likely to form material resembling rocks or meteorites.

When these accumulating bodies become massive enough, they will capture large amounts of gas from the primitive nebula. This is presumably the way in which Jupiter and Saturn were formed. The mean densities of these planets are very low, and it is evident that the great majority of their mass consists of hydrogen and helium.

Between two and five astronomical units, there are no special features of the primitive nebula model which suggest why a major planetary body did not accumulate in the region of the asteroids. Perhaps there is something special associated with the accumulation process at small sizes which will inhibit rapid accumulation. This inhibition might result from loss of intrinsic magnetic moments in the small particles due to the high temperature, and possibly also to lack of a suitable sticky surface necessary to hold particles together when they do collide.

In the inner solar system it is evident that accumulation once again becomes somewhat more efficient, but only for the accumulation of rocky types of bodies. However, these bodies evidently do not succeed in capturing gas masses from the primitive solar nebula comparable to those of Jupiter or Saturn. This is probably due to the high intrinsic temperature to be expected for the accumulating planets, which we discuss shortly, and the much higher temperature in the surrounding gas, which leads to greater characteristic turbulent velocities in the vicinity of the planets and hence to inefficiency in the capture of any extensive gaseous atmosphere.

The innermost planet, Mercury, has an extraordinarily high mean density for such a small body, which almost certainly indicates a large relative overabundance of iron compared to chondritic or terrestrial composition. This planet forms in a region of the primitive nebula where the pressure is high enough so that there is an interval of between 100° and 200°K in the cooling of the nebula gases where free iron may have condensed out, but where the principal magnesium silicates have not yet commenced their condensation. It is interesting to speculate that most of the small chemically condensed bodies which accumulated into Mercury may have condensed and accumulated while the gas temperature was in this intermediate range in the inner parts of the solar system.

One thing seems fairly certain regarding the accumulation in such a short time of a body the size of the earth. It must have been exceedingly hot initially. This conclusion follows if one assumes that the accumulation of the body has happened via either of two extreme processes. In one process, a central planetary nucleus might accumulate a large swarm of smaller particles, gradually increasing in size as these particles settle on to the surface. The released gravitational potential energy will largely be radiated away from the planetary body as the accumulation occurs, but, for an accumulation time scale comparable to the dissipation time of the nebula, temperatures in the interior approaching 10^4°K will be produced. Even higher temperatures will be produced if the accumulation occurred in the opposite extreme, via a hierarchal series of collisions. In such a series, bodies of a given size collide to form larger bodies, these bodies of the larger size collide to form still larger ones, and so on until something like a collision between two half-earths occurs to form the earth. This process would likely raise the temperature in the interior of the earth to 2×10^4°K or higher.

Needless to say, at these high temperatures rocky materials are completely converted into gas. The interior of the earth might be solid or liquid under these conditions, but the entire outer layers must be formed from the gases which result from the evaporation of silicates at high temperatures and their further thermal decomposition. In the case of the earth, this outer gaseous silicate atmosphere may very well extend to distances of 5 or 10 earth radii. I rather suspect that some aspects of the hierarchal collision process must necessarily be true, because in such a process the collisions are unlikely to be centrally head-on, and hence a considerable amount of spin will be imparted to the amalgamated body. The present angular momentum of the earth-moon system is easily obtained in such a non-central collision. In a case such as this, the spinning earth would reach rotational instability at distances in the equatorial plane of about 3 earth radii, so that gases at larger distances would necessarily go into orbital motion in the form of a disk. However, silicate gases would cool very quickly under these circumstances and condense, forming a series of lumps in the plane of the earth's equator, and I believe it quite possible that this was the basic mechanism leading to the formation of the moon from these large lumps left in earth orbit. Beyond 3 earth radii, the particles would be beyond the earth's Roche limit, and hence would be able to collect under their own gravitational forces.

This mechanism is consistent with a general low iron content for the moon. In a series of hierarchal collisions, the bodies which partake of the penultimate collision will themselves have been rendered exceedingly hot by the collisions which form them, and hence are likely to have a gaseous silicate atmosphere. The iron in such bodies should long since have condensed out of such an atmosphere and have settled toward the centers of these bodies. Thus the bulk of the free iron will be delivered to the center of the earth. The atmosphere will be basically silicates, and the moon is thus likely to be greatly depleted in free iron at the time of its formation.

On this picture both the moon and the earth would be greatly depleted in volatile materials. However, meanwhile the dissipation process in the solar nebula will have been forming the sun, and the T Tauri phase solar wind will commence. When this sweeps away the gas in the primitive nebula, it will leave behind a wide variety of chemically condensed materials covering a very large range of sizes from planets on down to metric-sized bodies or smaller. These will be left in essentially circular orbits, as will be the primitive earth-moon system. Such bodies with radial distances nearly the same as the earth will have a very small relative velocity with respect to the earth-moon system, and under these conditions the gravitational capture cross section of the earth enhances the geometric cross section very much more than would be the case for the moon. Thus the bulk of the volatile materials colliding with the earth-moon system will in fact be accumulated by the earth rather than by the moon. In this way, the earth may acquire a surface veneer of volatile materials which have contributed to a great extent to the earth's crust.

If one of these swept-up bodies should be fairly massive, when it collides with the earth in a non-central collision, there will be a significant perturbation in the earth's spin axis with regard to the original axis defining the plane in which the moon was formed. This suffices to tilt the earth's axis, with regard to the plane of the moon's orbit, thus accounting for what has seemed to be the apparent difficulty that the plane of the moon's orbit does not coincide with the earth's equator.

I have been informed by K. K. Turekian that he has estimated that the thin veneer needed to be added to the surface of the earth by the sweep-up process, to account for the volatile element content of the earth, amounts to about 10 per cent of the mass.