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THE ORIGIN OF METEORITES

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1. INTRODUCTION

A large number of solids and particles, from countless dust particles with diameter of a fraction of a micron to boulders hundreds of meters or even kilometers in diameter, move in interplanetary space. The smallest dust particles are stopped high in the atmosphere even before they have a chance to burn up, but when they drop to the earth's surface, they cannot in the majority of cases be distinguished from the earth's dust. Even a very expensive gathering of cosmic dust in the upper layers of the atmosphere yields only negligible amounts of matter. The larger particles are destroyed and evaporate in the atmosphere, producing short-duration meteor flashes or, if their dimensions are large, the more striking flight of "fire balls"—bolides.

If the object has a diameter from several centimeters to a few meters, and if it has sufficient mechanical strength and at the same time a small geocentric velocity (not > 20—25 km/sec), it is not fully destroyed in the atmosphere, and in such cases the flight of the bolide is completed by the fall of one or several meteorites—fused on the outside but unchanged inside, a remnant of a cosmic object entering into the earth's atmosphere. The earth encounters larger objects very rarely. Furthermore, such objects pass without obstacle through the atmosphere and upon striking the surface produce an explosion which destroys the object itself and results in a crater.

Thus, the main source of cosmic matter which reaches us are meteorites.

During the last decades the scientific significance and role of research on meteorites and their origin have changed appreciably. At the beginning of our century, during the time of erroneous notions concerning hyperbolic velocities of bolides and the interstellar origin of meteorites, the latter were regarded simply as examples of cosmic evolution of matter. When it became clear that meteorites are members of the solar system, produced together with the entire system (as was already thought in the nineteenth century), they became a most important source of information on the earlier stages of the formation of this system. In addition, they became sources of information on the "cosmic" abundance of nonvolatile elements for the recently developing research on nuclear genesis, and also a source of information on nuclear reactions occurring under the influence of cosmic rays.

The use of data on meteorites in the above two fields is based on the knowledge of at least the bare outlines of the history of meteorites and, in turn, yields many valuable data for the clarification of their origin. Moreover, investigations of meteorites have made possible two new approaches to the study of the origin of the solar system. Supplementing the classical approach, which has been in existence since Kant's time, in which a clarification of the process whereby the system was formed is based primarily on its mechanical properties, and the remaining properties serve for a subsequent refinement of the course of the process, there appeared an approach based primarily on the physical-chemical properties of the bodies contained in the system, and also an approach in which the conditions existing during the time of formation of the solar system are sought on the basis of analysis of data on the abundance of elements and on their isotopic ratios from the point of view of nuclear physics. The physical-chemical approach was initiated about 1950 in the work of H. Urey, while the nuclear approach appears for the time being only in the papers of Greenstein, Fowler, and Hoyle of 1962.

Meteorites can be investigated in laboratories in just as much detail as earth mineral rocks. However, the earth mineral rock available to us is the product of differentiation of the interior and subsequent reworking on the surface of the earth. On the other hand, the composition and structure of meteorites, especially of some types, have changed much less after their formation, and therefore characterize much better the protoplanetary matter.

The quantity of factual data on meteorites is already tremendous, and continues to grow at an ever increasing rate.* However, according to a remark by Brown, we are at such a stage of accumulation of knowledge, in which an increase in the reserve of factual information does not reduce but, to the contrary, increases the difficulty in understanding the origin of meteorites. The author proposes that this situation is due to the age-long dominance of two ideas, which he believes to be incorrect: (a) the ideas that the meteorites were produced in molten and differentiating interiors of some earth-like body or bodies; therefore, all efforts were directed at finding some sort of magmatic or "blast furnace" processes to explain the stone or iron

*Recently the most interesting data have been accumulated by means of new methods: isotopic analysis, analysis of scattered elements by neutron activation, x-ray microchemical analysis.

meteorites respectively (exceptions were made only for carbon chondrites); b) the ideas that the meteorites which we have collected present a "representative cross section" of some single or perhaps typical primordial body. The hypnotic effect of these two incorrect ideas has narrowed down the region of search and became the principal cause why we still do not have to date a theory explaining the origin of meteorites.

In addition, the actual data on meteorites pertain to different sciences: astronomy, mineralogy, chemistry, nuclear physics, etc, and there is no single encyclopedically educated scientist who could evaluate and synthesize them critically. Those who investigate meteorites, quite cautious in their fields, sometimes advance very bold, almost fantastic, ideas in associated fields of science. They frequently change their opinions concerning the origin of meteorites or simultaneously advance several alternate hypotheses.

2. METEORITES AND ASTEROIDS

The "nearest relatives" of meteorites are asteroids or, as they are otherwise called, small planets. The largest asteroids have diameters of hundreds of kilometers, while the smallest ones which can be observed (but only when they come close to the earth) have diameters 1—2 kilometers. There is no doubt, however, that there exist even smaller asteroids which serve as a continuous transition to the giant meteorites. The orbits of the majority of the asteroids lie between the orbits of Mars and Jupiter, but there are also some which enter inside the orbit of Venus in the perihelion or move out to the orbit of Jupiter in the aphelion. So far orbits have been determined for less than 2000 asteroids. From examination of weak asteroids with the aid of the largest telescopes it is concluded that the total number of asteroids which can be observed reaches 50—60 thousand.

At the present time, it is generally agreed that meteorites are fragments of asteroids produced when the latter collide. But this does not mean that all the asteroids which exist at present are the parent bodies of the meteorites, that is, bodies within which they were synthesized and acquired their composition and structure. The majority of modern asteroids are too small to have the necessary thermal history. Many of them experience oscillations in brilliance, indicating that they are angular fragments of larger bodies.

There are many indications pointing to a very close relationship between meteorites and asteroids.

Statistical investigations of the distribution of meteorite radiants[1-4] (that is, the directions of their geocentric velocity), conclusions based on the physical theory of meteors,[2] and also the best determinations of orbits by visual observations[5] have shown that meteorites move along short-period orbits and come from the asteroid belt. This was recently confirmed by the first exact determination of the orbit of the Prybram meteorite by means of photographic observation.[6]

The existence of a large number of asteroids moving along crossing paths, modified by planetary perturbations, unavoidably leads to collisions between these bodies. The collision probability is sufficiently large to assure collisions an important role. For the ten largest asteroids, Kuiper[7] calculated that the probability of collision of any of them in 3×10^9 years is 0.1. According to calculations by Piotrovsky[8], for a typical asteroid the average lifetime between collisions is 10^8—10^9 years. In the presence of tens of thousands of asteroids, collisions should occur every 10^4—10^5 years. This is confirmed by the existence of families of asteroids, discovered by Hirayama, and having according to the latest estimates[9] a lifetime of approximately 10^6 years. These families result from collisions of relatively large asteroids.

In order for a fragment to encounter the earth, it does not need at all to have at the outset an orbit that crosses that of the earth. It is sufficient that its orbit have a perihelion distance $q \leq 1$ a.u. Because of changes in such an orbit under the influence of planetary perturbations, the fragment will sooner or later collide with the earth (or with Mars). The average lifetime, calculated for bodies moving along orbits crossing that of the earth and having an aphelion in the asteroid belt is on the order of 10^8 years.[10] It agrees in order of magnitude with the so-called "cosmic ages" of meteorites, which give the duration of their bombardment by cosmic rays in the form of small bodies of the dimensions of the order of meters or less, that is, which give a time interval from the instant of their cleavage from the parent body or total fracture of the latter. Cosmic ages, which are measured from the contents of the isotopes that result from a nuclear fission process, amount to 10^6—10^9 years.[11]*

Data on cosmic ages have one unexplained feature: the ages of stone meteorites are on the average one order of magnitude lower than the ages of iron meteorites (10^6—10^8 and 10^8—10^9 years, respectively). To explain this, Urey [13] advanced the hypothesis that the iron meteorites come from the asteroid belt and the stone ones from the moon, and have therefore smaller ages. However, after the exact orbit was determined for the stone meteorite Prybram, and its aphelion was found to lie in the asteroid belt[6], Urey retracted his hypothesis. The systematic differences in ages could be attributed to different rates of erosion of the stone

*For two stone meteorites, Cold Bokkeveld and Farmington, it was found that they fell on earth more than 200,000 years after separation from the parent bodies.[12]

and iron meteorites under the influence of the "solar wind," cosmic dust, and larger particles.[14-17] However, experiments on the bombardment of meteorites with He^+, Ne^+, and Ar^+ ions have shown that stone meteorites are destroyed no faster than iron ones.[17a] At the same time, the lack of correlation in stone meteorites between cosmic age and brittleness does not confirm the hypothesis concerning the important role played by erosion due to impact of cosmic dust.

At one time it was impossible to explain the existence of groups of meteorites with similar cosmic ages, indicating that they might have been produced during the same act of disintegration of an asteroid. It might seem that the high frequency of collisions should lead to a practically continuous sequence of ages. What was lost from sight was that by far not every collision gives rise to fragments which enter into the region of the earth's orbit. The relative velocities of the asteroids are small, and therefore their typical collisions do not lead to the appearance of similar orbits.[18,19] In some cases, however, fragments are produced, ranging in size from meteorites to small asteroids, and coming close to the orbit of Mars. The number of small bodies with similar orbits is supplemented by rare collisions of these relatively few "Martian" asteroids. Under the influence of perturbations due to Mars, some of these bodies acquire orbits which come close to that of the earth, that is, they become capable of colliding with the earth.[20]

Only practically central collisions of bodies of similar dimensions can lead to total destruction of both. Collisions of small asteroids with large ones should produce on the latter impact craters, similar to those existing on the earth and on the moon. A large volume of matter under the bottom of the crater should be compressed and heated by a shock wave, pulverized, and partially mixed with the matter of the striking body. At almost glancing collisions, the cutting off of outer layers should accelerate the cooling of the remaining exposed layers.

The deduction that asteroids (principally those crossing the orbit of Mars) are the direct predecessors of meteorites solves the problem of their origin as individual relatively small bodies. At the same time, the problem of the origin of meteoritic matter coincides with the problem of the origin and development of the asteroids. In the interiors of these bodies, the meteoritic matter has spent the greater part of its life. The ages of meteorites, determined from the nonvolatile products of disintegration and characterizing the time from the instant of the formation of the solid meteoritic matter, amount to approximately 4.5×10^9 years.[11] They are somewhat longer than the "cosmic" ages and, according to a commonly held opinion, characterize the age of the solar system measured from the start of formation of the planets.

The key to the solution of the problem of the parent body or of bodies of meteorites must be sought among data on the chemical and mineralogical composition of the meteorites and on their structures and properties, and also in general considerations on the origin of the solar system.

3. ATMOSPHERIC SELECTION

The study of the origin of meteorites is based on data on meteorites falling on earth and reaching our hands. However, in order for a meteorite not to be completely destroyed during the time it flies through the earth's atmosphere, it must have sufficient mechanical strength.[21,22] The existence of bolides, the flight of which does not end in the falling of meteorites and which have sometimes in addition noticeable angular dimensions as a result of disintegration into a whole swarm of objects, indicates that by far not all the large meteoritic bodies withstand this test of strength. At the same time, not only is the strength of iron meteorites larger than that of stone ones; in stone meteorites, one observes a dependence between the structure and the strength, in that the strongest are the meteorites which have become recrystallized. Therefore, the author has been advancing for a long time the hypothesis that meteorites that are even more brittle than the most brittle meteorites in our collections exist in interplanetary space; because of their brittleness such meteorites never survive the flight through the atmosphere and do not reach us.

However, even among the mechanically strong meteorites, not all types are known to us. From time to time, one finds meteorites with an unusual structure or properties. Some types are known only in the form of inclusions in polymictic breccia meteorites (see Sec. 5), but have not yet reached us in the form of independent meteorites.[23]

Therefore, in clarifying the origin of meteorites, we should, of course, explain the origin of meteoritic matter of those types which we have in our collections, but should not assume at the same time that the parent bodies consist only of the substance of these types, and that they contain these types in the same proportions as in our museums.

4. COSMOGONICAL CONSIDERATIONS

The changes which have taken place in the general ideas of planetary cosmogony in the last decades are of very great significance for theories of the origin of meteorites and asteroids. During the time of dominance of the theories which have regarded planets as being formed from incandescent gas clusters, the hypothesis concerning one large primordial planet (for meteorites and asteroids) was natural, since the formation of small gas clusters is impossible. Now, when the principal structural material is assumed to be of solid particles, this difficulty has disappeared. Moreover, in the theories of O. Yu. Shmidt, Urey, and Hoyle, the formation of the large number of bodies

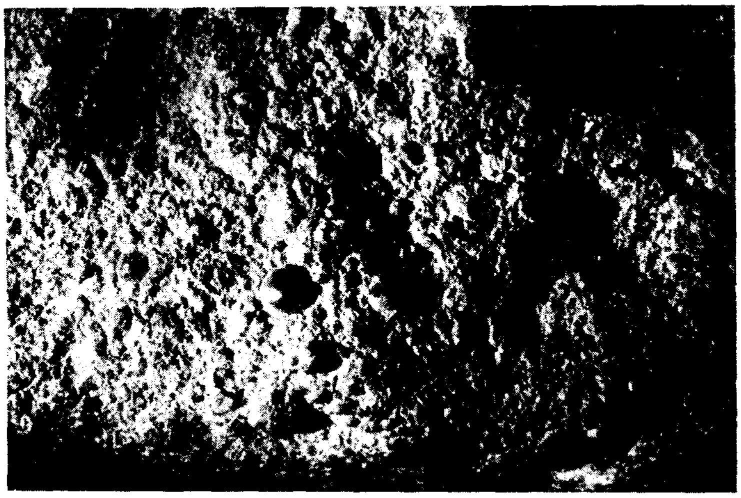

FIG. 1. The Saratov chondrite. The chondrules bordering on the surface of the fracture (× 10). At the corner–part of the outer surface with the melting crust.

with asteroid dimensions is an unavoidable stage of evolution, intermediate between the protoplanetary cloud and present-day planets.*

The existence of almost continuous transitions between the main types of meteorites—stone, iron-stone, and iron—was frequently considered as proof of a single primordial planet. These transitions, however, remain natural also if there existed many similar primordial bodies, each of which has given rise to meteorites of different types.[22]

Another very important consequence of modern cosmogonical theories is the understanding of the special position of the asteroid belt on the boundary between the zones of the earth-type planets and the giant planets.[24,24a] During an earlier stage of the solar system, when a non-transparent gas-dust nebula still existed, the zone of asteroids pertained to the outer cold region, where icy bodies accumulated. Later, when the accumulation of dust into asteroidal bodies cleared the space, the asteroidal zone became the external part of the region of earth-like planets, heated by the solar radiation. The initial content of volatile matter in the parent bodies of the asteroids and meteorites could be very large, almost the same as in the icy nuclei of the comets.[25] It is possible that to explain the origin of some of the most firmly established groups of meteorites it will be especially useful to consider such icy parent bodies not as ices of volatile matter in which nonvolatile particles are intruded, but as an amorphous disordered mixture of volatile and nonvolatile molecules and atoms.[26]

The special boundary position of the zone of the asteroids uncovers certain possibilities of explaining suspected differences in the chemical composition of the parent bodies (see Sec. 5). They can be due to condensation of primary solid particles at different temperatures (closer to the internal or external edge of the asteroid zone), or to some chemical separation which could accompany a large loss of volatile matter.

5. SOME PROPERTIES OF METEORITES

The main mineralogical component parts of meteorites are iron-magnesium silicates [principally olivines (Mg, Fe)SiO_4 and orthopyroxenes (Mg, Fe)SiO_3] and a nickel-iron alloy (on the average 90% iron and 10% nickel). More than 40 different minerals have been found in meteorites, and their number continues to increase. At least seven of them have not been observed in earth mineral rocks.[27]

Approximately 92% of the meteorites observed after falling are stone (containing up to 30% nickel iron), about 2% are stony-iron (on the average 50% silicates and 50% nickel iron), and about 6% are iron.* By weight, they constitute 85%, 5%, and 10% respectively (meteorites weighing more than 150 kilograms are too few for statistical treatment and have been discarded.[29]

Approximately 90% of the stone meteorites, that is, more than 80% of all the meteorites, are chondrites (Fig. 1). They contain chondrules, which are round silicate particles approximately 1 millimeter (up to 3–5 millimeters) in diameter, consisting of crystalline minerals (predominantly olivine or pyroxene) and glasses (Fig. 2). The meteorites with chondrite structure have been subjected to various degrees of thermal metamorphosis. This is manifest in the different degree of crystallization (or recrystallization) of the chondrules and of the fine-grain intruded matter. In strongly metamorphized chondrites, the boundary between the chondrules and the intruded matter practically disappears.[30-33]

Compared with earth rocks, chondrites have re-

*In 1956 Urey changed his point of view for reasons which the author considers unconvincing, and started to consider in place of bodies with asteroid dimensions bodies with lunar dimensions, that is, with diameter not of hundreds but of thousands of kilometers.

*Usually iron meteorites contain only small amounts of accessory minerals, but sometimes one encounters those containing as much as 10 – 20% silicates (see, for example,[28]).

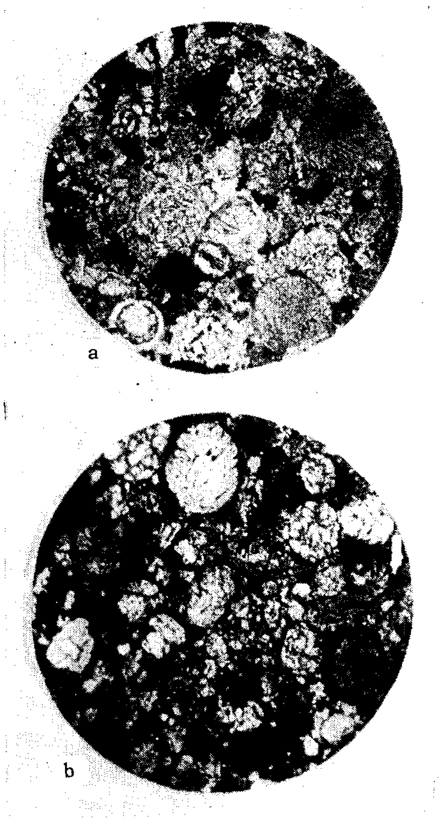

FIG. 2. Microphotographs of thin polished sections of meterites with chondrules of various types. a) the Aleksandrovskii khutor chondrite, d = 3.5 mm; b) Manych chondrite (× 12).

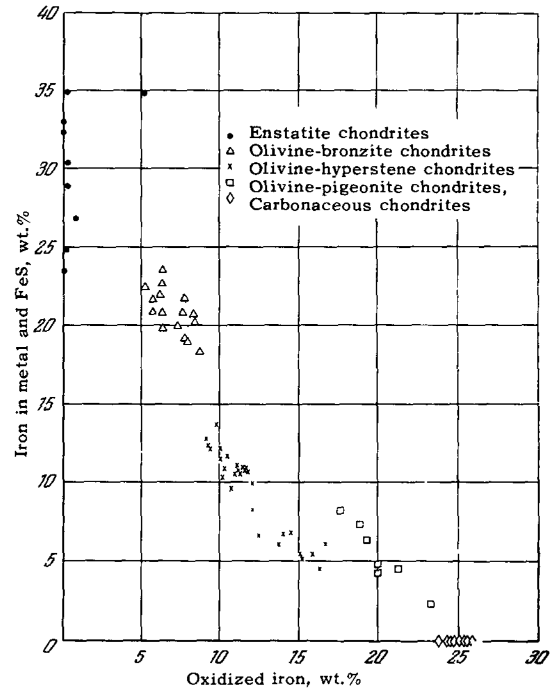

FIG. 3. Relation between the content of oxidized iron and iron in metal and sulfide in chondrites, showing the separation into individual groups and variations within the groups (Mason, 1962). Mason, like many others, regards the iron in the sulfide (troilite) as being reduced iron.

markably uniform chemical and mineralogical composition. The chemical homogeneity is particularly strongly pronounced in the nonvolatile elements, that is, when the analyses have been recalculated to exclude water, carbon, oxygen, and sulfur.[34,35,27]

From the point of view of physical chemistry, it is very important that the meteorites contain both oxidized and metallic irons. Prior has established in 1916 two laws for chondrites, which he unified in a single statement: "The smaller the content of nickel iron in the chondrites, the richer it is in nickel and the richer the magnesium silicates are in iron." This shows that the oxidation-reduction relations determine the compositions of these meteorites, which have been produced from practically uniform initial material.

During the time when the predominant idea was that the planets were made from hot solar gases containing much hydrogen, it was natural to assume that in the initial state the matter was completely reduced and therefore Prior explained the "laws" discovered by him as being due to gradual separation of the meteorites from the magma passing through different stages of oxidation. However, the situation changed during the last few decades, when it became clear that the planetary system was produced not from a cold protoplanetary cloud. Latimer[36] and Urey[37] have shown that the primary nonvolatile substances must have been fully oxidized in the presence of gases of solar or "cosmic" composition at low temperatures. Therefore at present the different content of metal in the chondrites is attributed to a different degree of reduction of the initially oxidized matter. It is assumed here that the reduction is produced not by hydrogen, but by carbon and by hydrocarbons, which still exist in carbonaceous chondrites.

In recent years general interest has shifted towards the symptoms that indicate the existence of several individual groups of chondrites. In 1953, Urey and Craig[38] discarded the unreliable analysis of the chondrites, and observed the existence of two groups with low (L) and high (H) total content of iron—22 and 28% by weight, respectively. They decided that these groups consist of fragments of two parent bodies. Later, on the basis the most reliable chemical analysis, it was established that five groups of chondrites, separated previously on the basis of their mineralogical composition, are clearly distinct from one another in the nickel and cobalt contents, and also with respect to the ratio of the metallic and oxidized iron (Fig. 3).[27,39,40] From the olivine-hypersthene chondrites* there was separated still another group of so-called amphoterite chondrites, or the group of Soko-Banja.[41-44,44a,19]

*The names of the groups, proposed by Mason (see Fig. 3), are rejected by Craig[44a] as being inconsistent with the terminology used in the petrology of terrestrial igneous rocks.

A very important fact is that in olivine-bronzite and olivine-hypersthene chondrites the minerals are almost in the state of chemical equilibrium. For example, they contain olivines with almost identical iron content.[40,35,27,45] However, olivine-pigeonite and carbonaceous chondrites are nonequilibrium. They contain olivines of various compositions and in the latter, furthermore, there is no equilibrium whatever between the chondrules and the intruding matter.[40,33,27,45,19]

The disclosure of groups of chondrites which are separated from one another by appreciable gaps, has cast doubt on the correctness of the "Prior laws." Inasmuch as the aggregate of the groups is arranged in Fig. 3 in a band corresponding approximately to the constant total content of iron, some authors believe that this confirms at least Prior's first law, which relates the content of oxidized and metallic iron. Other workers, however, (Yavnel',[41] Suess,[24a] Craig,[44a]) show, by means of analysis of continuously increasing accuracy, that within the limits of each group the content of the iron oxide both in olivine and in pyroxene is practically constant and does not correlate with the content of metallic iron in the given meteorite. The fact that the points for the meteorites of individual groups are scattered in Fig. 3 along straight lines corresponding to a constant overall content of iron, is ascribed by Craig in part to errors in the analysis, and in part to oxidation during weathering processes on earth. This, however, can also be explained as being due to the different content of olivine and pyroxene (in olivine and pyroxene which are in equilibrium, the content of oxidized iron in olivine is larger than in pyroxene). It must be added that the "Prior's group law" is satisfied only approximately, inasmuch as there exist groups of meteorites with different total iron content.

The groups of olivine-bronzite and olivine-hypersthene chondrites are so homogeneous, that each of them probably consists of fragments of the same parent body or perhaps of fragments of the same layer of parent body. On the other hand, the enstatite chondrites differ strongly in their iron content, and the carbonaceous chondrites break up into groups with different content of volatile substances and different mineralogical composition (see below). Such an inhomogeneity of these groups gives grounds for assuming that each of them contains small samples from different parent bodies, or at least from different layers of the same body.

Reliable determinations of the contents of many elements, including scattered elements, investigated primarily by the method of neutron activation, have shown that some of them are contained in different groups of chondrites in quite varied amounts.[46-50,43,19] In addition, individual meteorites within the limits of each group display large differences in their content. The latter can be due to inhomogeneities of the initial matter, perhaps with sizes on the order of meters.

FIG. 4. Hobdo chondrite–polymitic breccia (× 1.8).

The distribution of lithophilic, siderophilic, and chalcophilic elements, having a tendency to concentrate in silicate, metallic, and sulfide (FeS) phases of meteoritic matter, frequently differs appreciably from what is expected.

Achondrites, that is, stone meteorites which do not have a chondrule structure, are more differentiated and more deeply crystalline than chrondrites. They contain little metallic nickel iron or none whatever. Some of them are similar to remolten silicate parts of chondrites, while others are similar to the silicate phase of iron-stone meteorites and in addition, show a similarity with some terrestrial mineral rocks.[27,50,51,19]

Many stone meteorites and some iron-stone meteorites are of the breccia type, that is, they do not have a scree structure.[23,50,52] Most of them consist of the same crushed and pressed matter (monomictic breccia). Others contain fragments of meteorites of several types (polymictic breccia; Fig. 4). The most interesting examples of polymictic breccia are Nechaevo —a fragmented iron meteorite (octahedrite) with inclusions of recrystallized chondrite,[3] and Bencubbin which is a mixture of fragments of achondrite and at least three types of chondrites included in metal.[53] Breccia meteorites undoubtedly were produced upon collision between parent bodies of meteorites.* Veined stone meteorites and meteorites with light-dark (spotty) structure are modifications of breccia meteorites. The material of the veins and of the dark parts has almost the same chemical composition as the light material, but has a fine-grained or glass-like

*Since 1949 the author has been of the opinion that breccia meteorites serve as an indication of repeated total destruction and repeated accumulation of asteroids.[54] Now, however, he believes that they can be attributed to a *mixing of two colliding bodies* or, perhaps, even mixing within a single body.

structure. According to the latest data,[55] the veins and the dark substance are produced by shock pressures of several hundred kilobars.*

The structures of iron meteorites are closely related with their nickel contents. The phase diagram for iron-nickel alloys makes it possible to explain these structures as being due to slow cooling of large single crystals of nickel iron from temperatures at which only the γ phase exists (above 500—800°C for the common nickel content in meteorites), through the $\gamma + \alpha$ region. In the equilibrium state the α phase, called kamacite, contains less nickel than the γ phase, called taenite.) Iron meteorites containing less than 6% nickel, cross the entire region of $\gamma + \alpha$, and reach the region of the pure α phase, that is, they are completely recrystallized into kamacite. In accordance with the type of their crystal lattice, they are called hexahedrites. Some of them have subsequently lost the hexahedral structure as a result of thermal metamorphism and have been transformed into nickel-poor ataxites. Most frequently encountered are iron meteorites containing from 6 to 14% nickel. They consist of kamacite and taenite (γ phase) which are separated to a considerable degree, and this is manifest in a Widmanstatten structure, which appears when the polished surface is etched. They are called octahedrites, since the kamacite bars duplicate the octahedral structure of the initial crystals of the gamma phase. With increasing content of nickel, the thickness of the kamacite bars decreases, and at 12—14% nickel the Widmanstatten pattern disappears. Iron meteorites with an even larger content of nickel form the group of nickel-rich ataxites. They consist of plessite, a fine-grain mixture of kamacite and taenite. The so-called Neumann lines, observed in kamacite of some iron meteorites, were formed under the influence of shock pressures exceeding 100 kilobars.[56,57]

X-ray microanalysis of the variations in the content of nickel across the bars of kamacite and taenite in the octahedrites,[58,59] in conjunction with data on the dependence of the diffusion coefficient on the temperature has shown that the cooling from the $\gamma/\gamma + \alpha$ boundary to 300—400°C lasted on the order of 10^7—10^8 years, that is, the rate of cooling was 1—10° in 10^6 years. However, there exist meteorites with exceedingly steep nickel concentration gradients, indicating, so to speak, a very rapid cooling on the order of 1000—10,000° in 10^6 years. It is most probable, however, that these steep gradients are connected with the formation of a Widmanstatten structure under conditions of supercooling by 100—200°.[60] The occurrence of primary large single crystals of taenite is usually attributed to crystallization of the slowly cooling melt of nickel iron. However, the Washington County meteorite contains irregularly shaped pores, which become noticeably rounded off when heated to 1300°C for 100 hours.[61]

Yavnel' separates the iron and stone meteorites into five groups with different contents of nickel in the metal, while Lovering, Nichiporuk, Chodos and Brown[62] observed four groups of iron meteorites with different contents of gallium and germanium. In spite of the greater solubility of these elements in taenite, compared with kamacite, their content decreases with increasing nickel content. This argues in favor of the fact that the meteorites of these groups were formed in different parent bodies, or at least in different parts of one body. Yavnel'[63] has shown that in octahedrites belonging to each of these four groups, the coarseness of the Widmanstatten structure is differently connected with the iron content (see also [19,50]). This is almost undoubtly due to the different rate of cooling. Similar differences are indicated by the appreciable overlap between the octahedrites and the nickel-rich ataxite with respect to the content of nickel.[63,64] Many nickel-rich ataxites are probably samples which have experienced too rapid a cooling for Widmanstatten structures to be able to form. The simplest explanation of this difference in thermal histories is the origin from parent bodies of various dimensions.

Whereas iron meteorites are representative of the hottest part of meteoritic matter, which at one time had temperatures higher than 700°C, the carbonaceous chondrites represent the other extreme—matter which was never heated above 200—300°C. They contain up to 20% water, up to 3.5% carbon, free sulfur, and unstable organic compounds (hydrocarbons).[65-67] In a piece of internally-stressed glass, found in the carbonaceous meteorite Mighei, these stresses dissipated after annealling at 206°C for 2 days.[68]

Wiik[34] divided carbonaceous chondrite into three types or classes. Type I includes the largest amount of volatile matter, and consists essentially of practically amorphous hydrated silicates (chlorite, or more likely serpentine). They contain neither chondrules nor olivine. In carbonaceous chondrites of type II which contain 10—15% of water, there is 10—30% olivine in the form of chondrules, but the bulk is made up of hydrated silicates. In meteorites of type III, which contain about 1% water, olivine and other dehydrated silicates predominate. They contain also small amounts of nickel iron.

*It became clear a few years ago that in meteorites with spotty structure the primeval inert gases, if they are contained in the given meteorite, are concentrated in the dark matter, which has been modified by shock pressure (concerning the presence of primeval gases in meteorites see the end of Sec. 5 below). The increased content of sulfur in the dark veins, suggested by Anders and his co-workers[25, 98, 19] is debatable. Recently, however, Reed observed[55a] a bismuth content increased by a factor of six times in the dark matter of the Pantar meteorite, while Wlocka observed in it a five-fold increase in carbon. There is a suspicion, however, that in this meteorite the difference between the light and dark matter does not reduce to the action of an impact.

Carbonaceous chondrites of type I have a composition very similar to that expected from solid matter condensed in a moderately cold nebula of solar composition.[69]* Moreover, the contents of scattered elements in carbonaceous chondrites almost coincides with their "cosmic" abundance, whereas in ordinary chondrites they are contained in greatly reduced amounts.[43,47-49] On the basis of these data, it is now assumed that of all the substances accessible to us at the present time, carbonaceous chondrites of type I are closest to the primeval matter from which the planets of the earth group were formed. At the same time, they are the most primordial type of meteorite.[43,48,49,53,66,67,70,27,50,19]†

A puzzling fact is that not only the most oxidized carbonaceous chondrites, but also the most reduced ones (see Fig. 3), the enstatite chondrites, contain scattered elements in "cosmic" amounts. In addition, meteorites of both these groups contain large amounts of *primordial inert gases*.

Some fifteen years ago, when the accuracy of measurements of isotopic composition was low, it was found that many chemical elements of the earth and in the meteorites (including uranium) have practically the same isotopic composition. This showed that they were made of the same sufficiently homogeneous substance. Later, when the measurement accuracy increased, it was found that the isotopic compositions of oxygen and sulfur from meteorites and from terrestrial ultrabasic rocks are similar and show no isotopic shifts similar to those observed in basalt and granite, that is, rocks which are the products of differentiation of ultrabasic rocks.[73] Some isotopic anomalies not connected with the short-lived radioactive elements were found for some elements (see [11,19,49]), but they have not yet been interpreted.

In 1956, Gerling and Levskiĭ[74] discovered the presence of surprisingly large amounts of inert gases in the achondrite Staroe Pes'yanoe. The amount and isotopic composition of the gases showed that they were in the main primordial. In subsequent years, many investigators established that primordial gases are present in small amounts in almost all of the ordinary chondrites, and in much larger amounts in carbonaceous and enstatite chondrites. The mechanism of their capture and the succeeding processes of isotopic separation with diffusion losses remain unclear[11,19,49] Investigations of primordial gases are very closely related with determinations of the ages of meteorites and with a study of isotopic anomalies which are generated by decaying short-lived radioactive elements.

6. HYPOTHESES OF "FIRE-LIQUID" ORIGIN OF METEORITES

For more than a century many scientists attempted to develop the hypothesis of Olbers of one large parent planet, which has for some reason broken up and given rise to the asteroids (and, according to his successors, also to the meteorites). In the middle of the nineteenth century it was assumed that this hypothesis is supported by the presumed similarity between the composition of meteorites of different types and the composition of the internal shells of the earth (assumptions concerning the latter were made in analogy with a blast furnace). It is precisely this assumption which has induced researchers of meteorites to search for magmatic or volcanic processes of their production.*

In recent years, the absence of plausible physical causes for the disintegration of a single planet, the discovery of groups of meteorites (Sec. 5), and the contemporary ideas concerning accumulation of planets have led to the assumption that there existed several parent planets, which could collide and destroy each other. Nonetheless, the parent planets were assumed to be almost identical. An attempt was usually made to explain all the singularities of individual meteorites by their being formed in one "typical" parent body.

The development of the parent planet was considered for a long time purely qualitatively. Only recently were attempts started to find quantitative indications that meteoritic matter was at one time under high pressure, that is, was in the interior of a rather large body.

We owe the first of these attempts to Brown and Patterson.[76] Starting from the distribution of nickel and some other elements between the metal and the silicate of stone meteorites, they attempted to show that these phases were at one time at equilibrium at

*However, as was emphasized many times by Urey, "it follows from modern astronomical observations that the ratio of iron to other abundant elements on the sun is approximately 2–5 times smaller than in carbonaceous chondrites."[43] The reason for this difference, as well as for the difference between the L and H groups of chondrites, is so far not clear.

† This initial hypothesis of Urey was later rejected by him, as soon as it became clear that carbonaceous chondrites do not have exactly the same constant content of nonvolatile elements which he expected.[46, 71] It was replaced by the idea that these meteorites came from ordinary chondrites by some hydrothermal changes, as was previously suggested by Zavaritskii.[30, 31] Several years ago Du Fresne and Anders[72] advanced a similar hypothesis concerning the formation of carbonaceous chondrites of types I and II as a result of the action of aqueous solutions on "high temperature" minerals such as olivine, pyroxene, and troilite, which forms something similar to the material of carbonaceous chondrites of type III. However, the accumulation of new data has caused Anders[49, 67] and Urey[43] to change their points of view.

*In addition, it has given a false steer to investigators of the internal structure of the earth by reinforcing the faith in the hypothesis of the iron core. (On the basis of much geophysical and cosmogonical proof, the author is an adherent of the Lodochnikov-Ramsey hypothesis, according to which the core consists of "metallized" silicates.[75])

a pressure 10^5-10^6 bar (at 2000–3000°). These calculations were extensively criticized.[77,38] An analogous attempt by Lovering[78] was based on the distribution of nickel among the metal and the silicate in pallasites and among the metal and the sulfide in iron meteorites. His calculations, however, were criticized by Urey,[79] and the data employed by him were criticized by Yavnel'.[80]

Another approach to this question is based on a metallurgical study of the structures of iron meteorites. For example, several authors[81–83] believe that there exists a rather sharp boundary between the octahedrites and nickel-rich ataxites near a nickel content of 12–13%. Using the phase diagram of nickel iron, they attempt to show that this boundary can be explained only in the case if the cooling of the nickel iron occurred at a pressure 10^5 bar. However, at such a pressure, the diffusion coefficient is so small, that the formation of Widmanstatten figures would take a time exceeding the age of the solar system.[84] In addition, there is no proof that all the iron meteorites are parts of one and the same nucleus of a parent planet, and therefore cooled at the same rate. To the contrary, as already noted in Sec. 5, the boundary between the octahedrites and the ataxites is actually not very sharp, and this points to a different rate of cooling of the different iron bodies.[63,64,19] This is also indicated by the difference in the gradient of concentration of nickel near the boundaries of kamacite and taenite in octahedrites.[60] It must be added that the phase diagrams for nickel iron at both low and high pressures are incapable of explaining the observed content of nickel in the kamacite and taenite.[83,85,86,19] It is assumed that this is due to the unknown influence of small impurities. But in this case, no reliable conclusions are possible on the basis of the phase diagram for pure nickel iron.

A thorough analysis of all the metallurgical arguments has led Anders[19] to the conclusion that "there are no longer convincing grounds for assuming the formation of iron meteorites at high pressures; to the contrary, all the available data seem to be in good agreement with the formation at low pressures, whereas the notion that the formation occurred at high pressures must be reinforced by many special artificial assumptions."

The proof of the existence of an iron core in the parent planet, based on the presence of pre-terrestrial magnetic moments in stone and iron meteorites, is utterly unconvincing.[85,87,88] These moments are interpreted by the investigators who observe them as being due to the magnetic field which was possessed by the parent bodies during the time of slow cooling. It is assumed that the source of this magnetic field was a molten iron core. This explanation was assumed also by Anders.[19,25] However, in order to produce a magnetic field, the nucleus would have had to be convective, and this is highly improbable in an iron core, which has practically no radioactive elements and is surrounded by a mantle made of silicates rich in these elements.*

It must be added that Urey generally does not agree with the notion that all metallic iron must be gathered in the iron core of the parent planet. He adheres to the general idea that the pallasites (iron-stony meteorites with metal in the form of a solid structure similar to honeycombs) have occurred in the boundary zone between the molten metal and the silicate, but indicates a sufficiently large ratio of the number of pallasites to iron meteorites. In order to explain this ratio as being the ratio of the volumes of the boundary zone to the region of the pure metal, Urey suggests that the iron meteorites were produced not in a large core, but in many centers of the metal, scattered over the entire volume of the parent body (the "raisin cake" model[84]). These centers should have had widely differing cooling rates. However, as shown by Anders,[19] the presence of numerous centers of molten metal would not lead to an increase in the total volume of the pallasite matter.

Starting with 1956, the presence of diamonds in meteorites was considered by Urey[84] (and also by Lovering[78] since 1957) as proof in favor of a large parent body. The pressure necessary for the diamond formation can exist in a stationary manner in bodies of lunar dimensions and larger. In 1961, Lipschutz and Anders[90] proposed an explanation that diamonds in meteorites were produced under the influence of shock pressures in collisions of asteroids or when meteorites struck the earth's surface. In 1963 Urey[91] agreed with the fact that the presence of diamonds cannot be regarded as proof of a large parent body. But in 1964 he returned to the same argument[92] referring to the article by Carter and Kennedy,[93] who insist on formation of meteoritic diamonds under conditions of static pressure.

In 1960, Ringwood[94] pointed out that cohenite $(Fe,Ni)_3C$, which is present in some iron meteorites, is unstable at a temperature of several hundred degrees. It is stabilized by pressure, and therefore Ringwood assumed that the iron meteorites containing cohenite cooled at a pressure exceeding 25 kbar. The suggestion of Lipschutz and Anders[90] that cohenite is stabilized by phosphorus was refuted by experiments.[95] Recently, however, Lipschutz and Anders[96] showed that pressure can only increase the decay time of cohenite by a factor of ten, whereas actually it existed for a time longer by a factor of $10^{10}-10^{11}$. Thus, the proposed role of pressure has been refuted. The slowing down of the decay is attributed by these

*The surprising magnetic properties of the Bondoc meteroite, on the surface of which there are tens of magnetic poles,[89] Anders (private communication) is inclined to attribute to its breccia (fractured) structure.

authors preferrably to the slowness of formation of nuclei in the large regular crystals of meteoritic cohenite. It is important to note that recently [97] tridymite—a modification of quartz, was discovered in the Kendall County iron meteorite; this substance is unstable at a pressure exceeding 3 kbar at any temperature.*

There are three major objections to the hypothesis of a large parent body or bodies (see also [98,19]).

1. The total mass of modern asteroids is only 0.03 of the moon's mass. This does not agree with the hypothesis of a parent body of lunar dimensions (and all the more of several such bodies). The disintegration of asteroids is too slow [8] to enable one to regard present day asteroids as small remnants.

2. As was emphasized many times by Urey, [84,99,100] the thermal history of a body of lunar dimensions does not agree with the proposed thermal history of the parent body of meteorites. The cooling of iron meteorites, in which Widmanstatten figures were formed, should have been sufficiently slow and consequently should have occurred within the parent body prior to its destruction. However, as shown by calculations, [37,101,102] the central parts of a body of lunar dimensions, if they were hot at any one time, should have remained molten to this very day* and are thus perfectly unsuitable as a place for the formation of iron meteorites. The difficulties increase even further if we recognize that the ages of the stone meteorites, determined from their content of gases of radiogenic origin and characterizing, from the point of view of the hypothesis of a large parent body, the time of its decay (accompanied by the loss of previously accumulated gases) are very large and amount to $(4.5-4.6) \times 10^9$ years. [11] They practically coincide with the age of the entire solar system and consequently, the disintegration of the parent planets should have occurred approximately 10^8 years after its formation. The very rapid heating of its interior can be tentatively ascribed to short-lived radioactive elements, but its cooling within such a short time interval is impossible.†

Recently Urey, who in the last ten years changed his point of view many times, himself hit upon this difficulty. In 1953—1954 he considered the formation of meteorites in asteroid bodies. In 1956, after he called attention to the diamonds in meteorites, he started to consider primordial parent bodies of lunar dimension, which were completely destroyed by collision, their fragments accumulating again into secondary bodies. [84,13] This hypothesis makes it possible to get around the difficulties with the thermal history. However, meteorites are not random collections of fragments, and therefore this idea was discarded and Urey again considered only one generation of parent bodies, but now having lunar dimensions. [91] The difficulties with the thermal history become even greater in the latest idea of Urey, since during the earlier stage of their existence the parent bodies of the meteorites became intensively heated from the outside, since they were at the center of massive compressing gas spheres. [92]

3. All attempts to explain the formation of chondrules and chondrites as being due to some form of volcanic activity are inconsistent. Although Fredriksson and Ringwood [103] succeeded in obtaining chondrule-like spheres, imitating in the laboratory volcanism of an explosive character, serious objections advanced by Wood [104] against the volcanic hypothesis remain in force. Ringwood [40] believes that meteorites at our disposal give a representative cross section of the parent planet. Some 90% of the stone meteorites falling now on earth are chondrites. But then it is impossible that the volcanism would convert into chondrites the entire silicate mantle of the parent planet (Mueller's recent hypothesis [105] concerning fire clouds* inside the parent bodies is almost fantastic.)

In order to avoid these difficulties, Urey [92] makes the opposite assumption, that our collections are highly nonrepresentative. The distortions introduced by atmospheric selection (Sec. 3) should decrease but never exaggerate the fraction of the chondrites, which are less strong than meteorites of other types. The distortions can be arbitrarily large, if it is assumed that the "Martian" asteroids, which are direct predecessors of the meteorites falling on earth (Sec. 2), are fragments of only certain layers of a large parent body. However, even the formation of a thin layer with a chondrite structure and composition is difficult to attribute to volcanic processes.

Urey recently returned [43] to his views of 1953, [38] according to which impacts of fragments of colliding parent bodies against the surface of the remaining bodies produced local heating and a splashing of silicate drops which cool in chondrules. To be sure, now, when describing this process, which in his opinion produces a surface layer of chondrite matter, Urey refers to the experiments of Fredriksson and Ringwood [103] involving laboratory simulation of explosive volcanism. It must be added that chondrules were

*The simplest formula $x = (kt)^{1/2}$ shows that after 5×10^9 years with a thermal conductivity of mineral rocks $k \approx 10^{-2}$ appreciable amounts of heat can move only over a distance of approximately several hundred kilometers, whereas bodies of lunar dimensions have a radius of thousands of kilometers (the radius of the moon is 1738 kilometers).

† The presence of tridymite in stone and iron-stony meteorites has been known for a long time, but these meteorites could be assumed to be fragments of outer shells of the parent planet.

*Fire clouds (nuées ardantes) are clouds of incandescent ashes, ejected during some volcanic eruptions (for example, in the eruption of Mont Pelet in 1902). The ashes are kept for a long time in a suspended state because of turbulent motion in the cloud, and flow down along the slope of the volcano like a liquid.

never found around meteoritic and explosive (artificial) craters on earth.

Attempts were made to explain the fire-liquid origin of meteorites, but not in large parent bodies, but in bodies of asteroid dimensions. Some ten years ago analyses of meteorites gave such large values of the contents of uranium and thorium in them, that the use of these values in mathematical calculations of the thermal history of asteroids has led to the conclusion that the long-lived radioactive elements were capable of melting the interiors of bodies with dimensions of 200 kilometers and more.[106] At that time it appeared that the asteroids of medium and large dimensions could serve as the place of formation of meteorites. However, calculations with present-day values of the contents of uranium, thorium and potassium have shown that the heat generated by these elements could melt only the interiors of bodies with dimensions larger than 1000 kilometers.[107]

Nonetheless, Anders and his co-workers succeeded in developing an idea concerning the formation of meteorites in bodies of asteroidal dimensions, having molten interiors.[25,98] They have ascribed this melting to the presence in the protoplanetary matter of short-lived radioactive isotopes (Al^{26}, Fe^{60}). (This idea was advanced by Urey in 1955, but later on he rejected it.) The formation of chondrules was ascribed by them to volcanic activity and they proposed a cyclic mechanism for the elimination of the chalcophilic elements from the chondrite shell. At the present time Anders himself[19] criticized this hypothesis and now prefers a different hypothesis for the formation of chondrites, based on the ideas of Wood (see Sec. 7).

As was already stated in Sec. 5, a few years ago Anders and Du Fresne assumed that hydrated minerals and carbonaceous chondrites were formed as the result of the action of aqueous solutions on "high temperature" minerals. In order to reconcile these ideas with the notion of parent bodies of asteroidal dimensions, incapable of supporting on their surface an atmosphere and a hydrosphere, they advanced[72] the idea of the "internal atmosphere" and the zone of liquid water inside parent bodies. In a body heated from the inside and having an outside temperature of approximately 150°K, there should exist a subsurface layer of permafrost, extending to a depth at which the temperature 273°K is reached. Deeper, in the temperature interval from 273 to ~ 400°K, liquid water can exist. The permafrost layer, which is self healing, can lead to the retention of the "internal atmosphere" and play an important role in the retention of the inert gases. The time of existence of such a layer constitutes from 10^6 years near the internal edge of the asteroid belt to 10^{10} years, that is, much longer than the age of the solar system, near the outer edge. This important idea of Anders and Du Fresne should be taken into account and used in all theories of the origin of meteorites.

7. HYPOTHESES OF THE PRIMORDIAL NATURE OF CHONDRULES

The difficulty with explaining the origin of chondrules and chondrites is major for the hypotheses considered in the preceding section. In searching for a way out of this situation, Slonimskiĭ and the author[98] proposed in 1957 a hypothesis that the chondrules were produced in the solar nebula by direct condensation of nonvolatile molecules into solid particles.* However, at low temperatures, when the formation of amorphous spheres is possible, condensation is nonselective. It is therefore difficult to explain the mineralogical purity of the chondrules and the origin of particles of nickel iron and tryolite, let along the origin of iron meteorites. Following Urey,[13,84,100,110] who proposed that iron-niclel inclusions in chondrites were not formed locally, the author[54] believed at that time that it is possible that they were formed somewhere even before the parent bodies of the chondrites and entered into the latter during the time of their accumulation. Thus, no attention was paid to Prior's rules. A positive feature of this hypothesis was that to explain the thermometamorphism in the chondrites it was necessary to assume only a moderate heating of the outer parts of the parent bodies, whereas more heated central parts of these bodies could be regarded as places of formation of some types of achondrites. However, this attempt was unsuccessful.

Recently, new investigations of metallic particles in meteorites, carried out by Kvasha,[111] Knox,[112] Ramdor,[113] and Anders[19] gave sufficiently convincing indications that the majority of these particles were formed locally. However, in some meteorites they are broken and are shifted from the place of their origin during the time of acquisition of the breccia structure.

In 1958 a second hypothesis of the primordial nature of chondrites was proposed by Wood.[114] In the first variant it was assumed that the liquid drops of the silicates and of the iron condensed during the time of cooling of the solar nebula. Later[104] a new calculation of the necessary temperatures and pressures in the nebula has shown that such a process is impossible, and it was admitted that condensation leads to the formation of strongly oxidized dust. It is assumed that part of the dust was again reheated and thereby reduced by the shock waves generated by powerful eruptions on the young sun, forming silicate and metallic drops which cooled later into chondrules and metallic particles. The strongly reduced chondrules plus the metal constituted the "high temperature" fraction of the primordial matter, from which the parent bodies of the meteorites accumulated, and the strongly oxidized dust constituted the "low-temperature" fraction of this matter. The

*In 1949, Suess[109] proposed the condensation of chondrules in a hot planetary atmosphere.

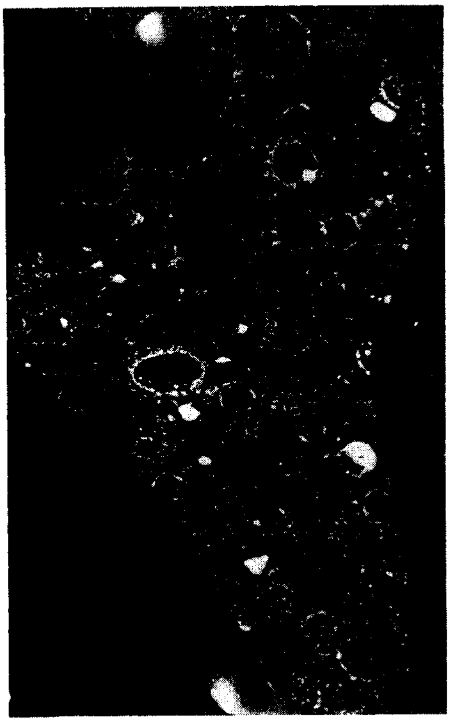

FIG. 5. Renazzo carbonaceous chondrite—the only one containing much nickel iron. Polished surface in reflected light. Numerous large chondrules, surrounded by rings of metallic grains are seen.

dust served as the enclosing matter for the chondrules and metal. According to Wood, the meteorite Renazzo (Fig. 5) is an almost unchanged non-equilibrium mixture of both these fractions, whereas carbonaceous chondrites of type I contain only practically pure enclosing matter. It is assumed that other chondrites contain different amounts of these two fractions and have experienced a larger or smaller thermometamorphism. The origin of iron and iron-stony meteorites and achondrites is explained in the usual manner, as a result of processes of fusion and differentiation in the parent bodies. Recently, Merrihue[115] found that the chondrules from the meteorite Bruderheim are enriched with excess xenon-129 and are poor in primordial xenon, as compared with the entire meteorite. This can be assumed to indicate that the chondrules were formed earlier than the parent bodies of the meteorites. There is no assurance, however, that this conclusion is correct. In the interpretation of isotopic anomalies of xenon there are many unclear factors.[11,49,119-116]

Since 1963, Anders[49,19] accepts Wood's scheme which he believes to be better. Nonetheless, he makes several critical remarks and admits that the accumulation of new data can lead to a change in this scheme.

The author of the present review considers it highly unlikely that shock waves in a protoplanetary cloud generated by solar eruptions, should pass through 300—500 millions of kilometers in a layer of dust, which has settled in the central plane of this cloud, reaching the zone in which the modern asteroids were produced.

8. HYPOTHESIS OF UNMOLTEN PARENT BODIES

In 1960, Mason[70] proposed a hypothesis that ordinary chondrites were formed of an original substance similar to carbonaceous chondrites of type I by dehydration and partial reduction at a temperature above 600°C. He assumed initially that the carbonaceous chondrites contain chlorite chondrules, which can become recrystallized in the solid state into olivine and pyroxene chondrules. Subsequent investigations have shown, however, that there exist no chlorite or serpentine chondrules and therefore he suggested spherulite crystallization of the olivine and pyroxene, replacing the amorphous serpentine matter.[117,27] Although olivine and pyroxene are minerals with high melting points, their presence does not necessarily mean formation at high temperature. Bowen and Tuttle[118] have shown that forsterite Mg_2SiO_4 can be produced from serpentine at a temperature below 400°C, and the thermodynamic data of Bennington[119] indicate that olivine and pyroxene can be produced from the enclosing matter of carbonaceous chondrites at moderate temperatures (olivine and serpentine coexist in thermodynamic equilibrium at low temperatures up to 200°C). Mason[117] noted that "in spite of the presence of a considerable amount of oxidized iron, olivine in carbonaceous chondrites of type II is practically or perfectly free of iron, which is characteristic of olivine produced as a result of thermal decomposition of serpentine." Mason in the book[27] calls the formation of chondrules a spherulitic crystallization; this has induced Wood[104] to write that Mason believes the chondrules to be porphyroblasts. This is the term used in geology for mineral formations which are the results of recrystallization in the solid state. However, the most primordial chondrules in carbonaceous chondrites and in other non-metamorphized chondrites are only partially crystalline. They contain glass and therefore cannot be regarded in the strict sense of the word to be the product of crystallization or recrystallization.

The existence of non-miscibility in silicate melts has been known for a long time, but its role in geochemical processes remains unclear. Recently, progress in the technology of manufacture of glass and glass ceramics (pyrocerams) has disclosed the important role of non-miscibility in glasses below the solidus temperature.[120,121] The separation of glass into two metastable liquids can occur not only in those cases when at higher temperatures two stable liquids can occur, but also when the field of the two liquids on

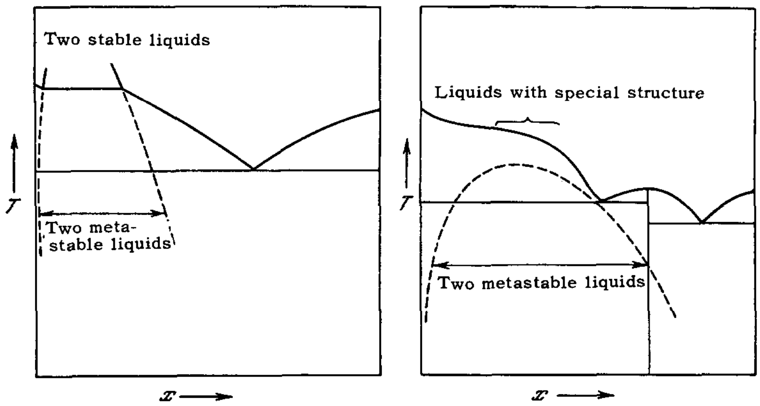

FIG. 6. Schematic representation of simple binary systems, in which two immiscible liquids can be metastably separated during heat treatment of glass below the solidus line.

the phase diagram does not rise above the liquidus line (Fig. 6). The small spheres produced in the laboratory in such a metastable separation are, like chondrules, partially glass and partially crystalline. Although the process of chondrule formation proposed by Mason includes dehydration and reduction, it appears to be more similar to such metastable separation of two non-miscible liquids than to spherulite crystallization.

Recently, Mueller[122,105] investigated the microstructure of carbonaceous chondrites, and his result so to speak confirmed the ideas of Mason. In carbonaceous chondrites of type I, he finds minute glass spheres and minute round crystallites of olivine, and sometimes of other "high temperature" minerals. Many of these spheres and crystallites contain small nuclei which are probably nickel iron and troilite. In carbonaceous chondrites of types II and III the amount and dimensions of these grains increase and there is a tendency of individual crystallites to combine with the nuclei and form larger spheres—chondrules. The nucleation and growth of numerous small spheres and their subsequent aggregation into chondrules is apparently in better agreement with the experimental data accumulated in the manufacture of glass.

If we omit those details, which call for further study, then we find that the general direction of evolution, proposed by Mason and assumed by the author of this article, is as follows: carbonaceous chondrites of type I (no chondrules) → carbonaceous chondrites of type II (chondrules produced as a result of decomposition of serpentine) → carbonaceous chondrules of type III (serpentine fully transformed into olivine plus pyroxene, but these "high temperature" minerals are still non-equilibrium) → ordinary chondrites ("high temperature" minerals in equilibrium). Mason includes enstatite achondrites in the last member of this series (see Fig. 3). However, the almost "cosmic" content in these meteorites of many scattered elements, which are lacking from ordinary chondrites, and the high content of primordial inert gases, gives grounds for assuming that they are possibly similar to carbonaceous chondrites of type III with respect to the stage of their development, but were formed in somewhat more reduced surroundings.*

A few years ago carbonaceous chondrites were believed by many authors to be the product of hydrothermal metamorphism of ordinary chondrites. This point of view has now been abandoned. Nonetheless, some structures which were pointed out as being the result of hydrothermal changes[30,31,72,124] are probably real. They can be attributed to the existence of an "internal atmosphere" and a layer of liquid water in some of the parent bodies (see Sec. 6).

The carbonaceous and ordinary chondrites which we now possess illustrate the general direction of the evolution, but are not "frozen" samples of successive stages of strictly one and the same evolutional path. In most carbonaceous chondrites of type II, the chondrules are larger than in carbonaceous chondrites of type III. The meteorite Renazzo is similar in its mineralogy and composition to the carbonaceous chondrites of type II, but it is unique in that it contains many large chondrules and approximately 12% of nickel iron.† The L and H groups of ordinary chondrites differ from each other in the over-all content of iron. Obviously, chondrites in our collections are samples of several parent bodies, differing somewhat in composition and in evolution.

Two important processes of thermal changes in meteorites, occurring in the solid state, are admitted by all: a) the transformation of the γ phase of nickel

*The difference in the surroundings is ascribed tentatively by Mason to the formation of meteorites at greatly differing distances from the sun.[45] This, however, contradicts the astronomical data. The special position of the asteroid belt on the boundary between the earth planets and the giant planets explains this diversity in the surrounding conditions (see Sec. 2) naturally.

† Whereas Wood[104] and Anders[19] regard Renazzo to be an example of almost unchanged primordial matter – a mixture of "high temperature" and "low temperature" fractions (see Sec. 7), Mason and Wiik[125] offer indications that the chondrules were apparently in the stage of growth when the process was "frozen." They believe that Renazzo constitutes a transition to enstatite chondrites.

iron into the α phase, accompanied in many cases by the formation of the Widmanstatten structure, and b) recrystallization of chondrites, accompanied by vanishing of the chondrules.* A third important process of the same type was proposed by Mason, namely, dehydration of serpentine, reduction of the iron, and formation of chondrules consisting of "high temperature" minerals. The author of the present article proposes to extend the field of action of diffusion and recrystallization processes in the solid state in such a way as to include practically the entire evolution of meteoritic matter and formation of meteorites of all types, including iron, iron-stony, and achondrites.[128] This process has occurred in many parent bodies of asteroidal dimensions, the largest of which were similar to the largest of the modern asteroids.

The formation of the Widmanstatten structure at 350–500°C lasted approximately 10^7–10^8 years. The diffusion coefficients depend strongly on the temperature and at higher temperatures much larger changes should occur within the same time interval. However, in order to determine fully the probable role of diffusion in the solid state, it is necessary to take into account the fact that the central parts of the largest asteroids were at temperatures 80–100°C for several hundred million years.[107]

If we imagine that the thermal changes of the chondrite matter have advanced further than the recrystallized chondrites, then we obviously arrive at some more modified and differentiated non-chondritic substance. Let us attempt to trace this using nickel iron as an example. In the carbonaceous chondrites of type III, the metallic iron is present in the form of small granules of several different dimensions. The greater solubility of the smaller grains, connected with the role of the surface energy (surface tension), causes the nickel iron to gather into large inclusions and the smaller inclusions are drawn away. This takes place (by diffusion in the solid state) during the time of transformation of the carbonaceous chondrites into ordinary chondrites. Although the surface tension tends to make the surface minimal, the metallic inclusions in the chondrites usually have a spongy form because of the greater plasticity of the metal compared with the silicates. Merrill (1928) noted that they are similar to spongy iron produced when iron ore is reduced at temperatures 700–800°C. In the chondrites the temperatures were probably lower, but the duration of the process was much longer.

In those parts of the parent bodies which reached temperatures of the order of 1000°C, the gathering of the nickel iron into larger and larger bodies could

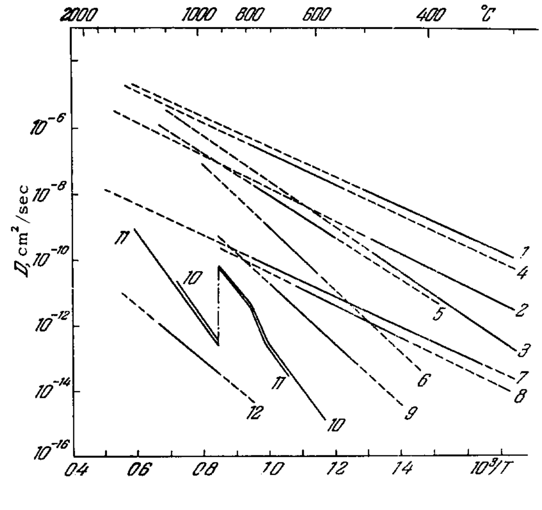

FIG. 7. Dependence of the coefficient of diffusion on the temperature 1 – lithium in quartz[129]; 2 – sodium in quartz[129]; 3 – potassium in quartz[129]; 4 – radium in albite[130]; 5 – radium in microclinic perthite[130]; 6 – lead in albite[130]; 7 – lead in microclinic perthite[130]; 8 – sulfur in iron[131]; 9 – phosphorus in steel[131]; 10 – nickel in iron[132]; 11 – iron in iron (self diffusion)[133]; 12 – iron in fosterite[134]. The rate of diffusion in crystals depends upon the direction. Lines 1 – 7 give D for the crystallographic direction in which the rate of diffusion at a temperature on the order of 1000°C is maximum. The solid lines show the temperature intervals in which the measurements were made.

go so far, that "inclusions" with dimensions of several meters were produced, that is, with the dimensions of the largest iron meteorites found on earth.* In order to attain this after 10^9 years, the coefficient of diffusion D should be of the order of 10^{-9}–10^{-10} cm²/sec. Actually, at 1000°C even larger values are obtained (Fig. 7).† The proposed slow growth insures formation of large γ-phase crystals.

Thus, the author believes like Urey, that the parent bodies are something like a "raisin cake," but, unlike Urey, he assumes that the iron inclusions were never molten.

*In iron meteorites, the separation of rhabdite $(Fe,Ni)_3P$, cohenite $(Fe,Ni)_3C$ and also small inclusions of troilite FeS was the result of the decay of supersaturated solid solutions of P, C, and S in nickel iron, that is, it was also proceeded by diffusion in the solid state.[126, 127]

*The presence in the Arizona meteorite crater and in its vicinity of a considerable amount of nickel iron induces many authors to assume that this crater was produced by impact of an iron meteorite with diameter of approximately 30 meters. It is assumed in analogy that even greater "meteoritic" craters were produced on earth by impact of iron bodies with diameters of hundreds of meters or even kilometers. However, these could perfectly well be stone bodies, small asteroids containing 10 – 20% iron inclusions.

†In Fig. 7, the only data on the diffusion of iron through silicates pertain to its diffusion through forsterite Mg_2SiO_4. They give low values of D. However, the measurements were made for very dense samples by sintering powder at 1600°C and approximately 1000 atmospheres. The diffusion of iron through very porous silicate matter of meteorites is apparently much faster. [We used data from a plot in[134]. The formula given in the text for D(T) gives values of D which are larger by a factor of 10, apparently as a result of a misprint.]

When the parent bodies collide and break up, the large iron inclusions should separate from the surrounding silicates because of the difference in the density and in the elastic properties. These surrounding silicates should be very highly differentiated and should be almost or completely free of nickel iron. Samples of this matter, apparently, are the achondrites. Indeed, as noted by Prior (1918), many achondrites are similar to the silicate parts of some iron-stony meteorites.

Iron-stony meteorites are apparently samples of matter in which the separation of the metal from the silicates stopped during some intermediate stage as a result of cooling. They were produced not in some diversion stage of the process, but during the main course of formation of the iron meteorites. When the silicates became locked inside the metal, those which could diffuse easier escaped, while those with poorer diffusion remained trapped. This was probably the process whereby the pallasites were formed. The predominance of olivine in pallasites is possibly due to its high melting point. At temperatures more than 500° below the melting point it probably has a small coefficient of diffusion, and possibly also small solubility in iron. Pallasites with rounded or sharp-corner grains of olivine could be formed at various temperatures lying in such an interval that the temperature dependences of the "crystallization force" and of the surface tension cross.

It is easy to understand that the diffusion of iron can transform a meteorite such as Mainsee (Fig. 8), with the metal scattered in the form of minute grains,

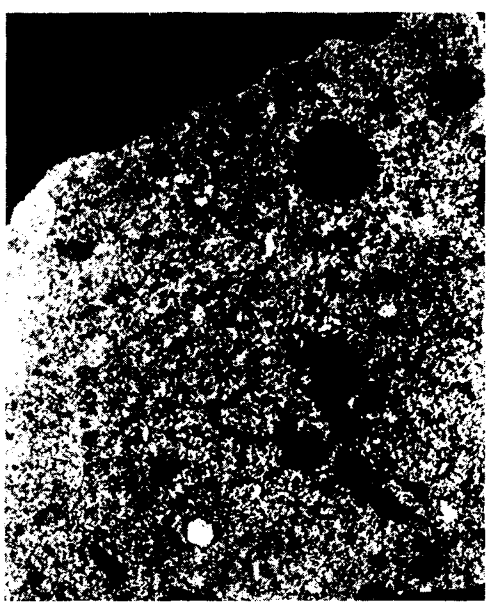

FIG. 8. Iron-stony meteorite Mainsee. The polished surface on which small grains of metallic iron (white) are seen scattered over the entire silicate enclosing substance.

FIG. 9. Iron-stony meteorite Esterville. The polished surface on which one can see that the nickel iron (white) has a tendency of forming clusters.

into another meteorite, similar to Esterville (Fig. 9) with the metal gathered into clusters. But the origin of the Mainsee meteorite itself is very difficult to understand. The only likely explanation is fractionalization with small subsequent metamorphism. (The existence of breccias among the iron-stony meteorites is well known.) It is usually assumed that the pallasites, and also large inclusions of troilite and graphite in metal, were produced in the melt. However, the rate of gravitational differentiation should be very large, even when the gravitation is small (Anders, private communication). On the other hand, the tendency to phase separation, which exists at the melt temperature, continues to exist in many cases even at lower temperatures. However, in the solid state it is necessary to have tremendous time intervals for this tendency of phase separation to manifest itself. Meteorites, and more probably the parent bodies of the meteorites, have a history which precisely satisfies the necessary conditions.

If large-scale diffusion processes took place in the parent bodies of the meteorites, then chemical separation by diffusion should have been highly effective. It is possible that this can explain the separation of the scattered elements in the meteorites, and also the variable character of the behavior of some of them with respect to the manifestation of lithophilic, siderophilic and chalcophilic properties. The latter can be attributed to differences in the surroundings and in the temperatures.

Thermal metamorphism, which occurred at different temperatures and over different time intervals, is a very flexible mechanism, which includes many processes, each having its own activation heat, that is, its own temperature dependence. This gives grounds for suggesting that the variety in the types and the structures of the meteorites can be attributed to differences in the thermal histories of the parent bodies and their individual layers.

The author hopes that a review of the interpretation of the observed properties of meteorites will confirm that diffusion in the solid state was a decisive process in the parent bodies, the interiors of which were never molten.

Unfortunately, these are only hopes for the future. The present day situation concerning the origin of meteorites still corresponds to the words of Wood [50]: "There are perhaps as many views on the origin of meteorites as there are investigators of meteorites. Probably in no other field of natural science is there such a combination of abundance of factual data and absence of accord in their interpretation." Tomorrow, however, that is, in the not too far future, the situation may become entirely different. Under the influence of new factual data, obtained with the aid of new precise methods of research, many established notions concerning meteorites are being reviewed, and there is a tendency for the views of individual scientists to come closer together. Scientists who work with meteorites are representatives of various branches of science. They employ different experimental methods and different theoretical approaches, and do not always readily understand each other. Therefore, this "tomorrow," when the tendencies to the drawing together of the views will lead to an considerable clarification of the origin of meteorites, will probably not take place before 3 to 5 years. This, however, is not such a long time.

9. SOME CONCLUSIONS

1. Meteorites are fragments of asteroids, produced when they collide. In turn, the majority of modern asteroids are fragments of larger parent bodies. Only the largest of the modern asteroids are surviving representatives of these primordial bodies. (There are scientists, however, who assume these asteroids to be fragments of even larger bodies.)

The evolution of meteoritic matter occurred in the largest "primordial" asteroids, with diameters of hundreds of kilometers (and in the opinion of some investigators, even in larger bodies) the interiors of which were heated to high temperatures by radiogenic heat. Thus, the problem of the origin and evolution of meteoritic matter is at the same time the problem of the origin and evolution of the asteroidal matter.

2. Typical collisions of typical asteroids, moving between the orbits of Mars and Jupiter, do not give rise to fragments whose orbits, evolving under the influence of only planetary perturbations, could subsequently cross the earth's orbit and cause the fragment to fall on earth. Such fragments can arise only upon collisions of asteroids entering inside the orbit of Mars, and it is just these which are the direct predecessors of the meteorites falling on earth. These few "Martian" asteroids are probably representatives of only a few of the primordial asteroids, and perhaps even of only some of their layers.

3. A dominant position was held for a long time by hypotheses that relate fully the occurrence of meteorites of all types with magmatic and volcanic processes in the interiors and on the surfaces of the parent bodies of lunar or even larger dimensions. In recent years, the main adherents of this point of view are Urey and Ringwood. However, the main evidence in favor of these hypotheses was refuted or placed under doubt. In addition, the adherents of these hypotheses did not succeed at all in explaining satisfactorily the occurrence of the chondrule structure possessed by 80% of the meteorites.

4. The radical changes occurring during the last decades in the cosmogonical ideas concerning the process of formation of the solar system have recently given rise to hypotheses which related directly some features of meteorites with the properties of the solid matter from which the parent bodies of the meteorites accumulated. This pertains primarily to carbonaceous chondrites, which contain carbon and hydrocarbons, water and free sulfur, and consisting essentially of amorphous hydrated silicates (of the serpentine type). Carbonaceous chondrites of type I containing the largest amount of volatile substances and containing no metallic iron, are presently assumed to be the most primordial type of meteorite, closest in composition and structure to the solid matter of the protoplanetary cloud.

5. Anders, developing Wood's ideas, suggests the existence of two fractions of initial matter: a) highly oxidized dust, which is the direct product of condensation of nonvolatile substances in the protoplanetary cloud, and consisting essentially of amorphous hydrated silicates, and b) dehydrated and reduced chondrules of olivine and pyroxene plus metallic particles. (According to Wood's hypothesis, the second fraction develops from the first when the latter is heated in a reducing hydrogen medium by shock waves generated by flares on the sun.) The existence of meteorites of various types is explained by the fact that these fractions are mixed in different proportions, and have been subsequently subjected to a different degree to thermal metamorphism or even to melting.

6. According to Mason's hypothesis, the formation of chondrules and metallic particles occurred at low temperatures, and already in the parent bodies accumulated from oxidized hydrated matter (similar to the first Wood-Anders fraction, and also to carbonaceous chondrites of type I). The dehydration of serpentine with formation of olivine, observed in the laboratory only at high temperatures, can occur according to thermodynamic data also at low temperatures, although of course very slowly. In parallel with the dehydration and spherulitic crystallization of the produced "high-temperature" minerals, there occurred reduction of the iron by the carbon and by the hydrocarbons. All these processes should have proceeded via diffusion in the solid matter.

7. While explaining successfully the formation of chondrites, Mason's hypothesis does not consider the origin of stone meteorites—achondrites, and also of iron and iron-stone meteorites. Developing Mason's point of view, the author has shown that in the interior parts of parent bodies, which were at a temperature on the order of 1000°C for a long time, the diffusion processes in the solid matter should have led to a considerable separation of the metallic and silicate phases. The gathering of the metal (nickel iron) into large inclusions, due to the action of surface tension (surface energy), has led to the formation of iron meteorites, while the surrounding silicate matter, rid of the metal and strongly changed in structure because of prolonged exposure to high temperatures, has formed achondrites. Wherever the reduction in temperature stopped the diffusion separation of the metal and silicate prior to its completion, iron-stone meteorites were produced.

Inasmuch as the chondrules contain as a rule larger or smaller amounts of glass, the author, unlike Mason, believes the process of their formation to be not spherulitic crystallization, but an analog of the separation of glass into two metastable liquids, made more complicated by processes of dehydration of the silicates and reduction of the iron.

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