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DIAMONDS, METEORITES, AND THE ORIGIN OF THE SOLAR SYSTEM

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ABSTRACT

In order to explain the chemical composition and physical structures of meteorites, it is proposed that two sets of objects of asteroidal and lunar size were accumulated and destroyed during the history of the solar system. These are referred to as the "primary" and "secondary" objects. Since diamonds occur in meteorites, some of the objects must have been of lunar mass or greater; but it is not possible to be certain as to whether this occurred in the primary or secondary objects. The ages of the meteorites require that the primary objects accumulated about 4.5×10^9 years ago, were heated by some means to the melting point of silicates and iron, were then cooled to $\sim 500°$ C for 10^7–10^8 years, and subsequent to this were broken into fragments of less than centimeter and millimeter sizes. The secondary objects accumulated from these about 4.3×10^9 years ago, and they were at least of asteroidal size. These objects were broken up at some time or times during the last 4.5×10^9 years, and the fragments are the meteorites. These collisional processes occurred during the formation of the solar system. The primary objects must have antedated the time of active formation of the system.

Solid objects appeared early during the formation of the system and played an important physical role during the formation of the planetary system and possibly in the formation of the sun. It is suggested that the solar nebula consisted of a disk of gas and solid objects and that the dissipation of the gases and some of the solids took place from this disk. Protoplanets in the sense of large masses of gas and dust of solar composition did not occur, at least in the case of the terrestrial planets, and not until much dissipation of the gases and dust had occurred.

Two problems relative to the origin of the solar system have been a source of much thought and speculation on the part of the author during the last six years. One has been the origin of the heating process which melted the metal and silicates of the meteorites, and the other the process by which a considerable fractionation of the silicate and metallic fractions of solar material occurred, as indicated by the varying densities of the planets. It has been assumed that these two processes were related to each other.

Chamberlain and Moulton first suggested that solid objects of considerable mass were an important feature of the origin of the solar system. Jeans and Jeffreys were not too definite about this point but introduced the concept of gas spheres formed by gravitational instability in a filament of gas which had been produced by tidal disruption of the sun. Eucken (1944) discussed the condensation of the planets by condensation of liquids from gases within Emden gas spheres. Von Weizsäcker (1944) proposed that the sun acquired a disk-shaped nebula during its early history and that this nebula broke up into a system of regular vortices and that the planets accumulated in secondary eddies between these vortices. Kuiper (1951) modified the previous discussions by assuming gravitational instability within a disk-shaped solar nebula as a source of gaseous spheres, which he called "protoplanets." Urey (1951) discussed the chemical problems associated with these models and tried to fit the chemical evidence into the protoplanet model. Throughout his discussion, these problems of the fractionation of the silicate and metallic constituents, the high-temperature melting of the silicate and metallic phases in meteorites, without any important fractionation of the more volatile from the less volatile elements, have been predominant. In fact, his arguments constitute the only, or at least the most compelling, argument for the existence of massive solid objects sufficiently large to be able to preserve the more volatile elements through some kind of high-temperature melting process during the early history of the solar system.

held more nearly that of the moon (165 dynes) than that of Ceres.

The kamacite and taenite are present in the Holbrook, Beardsley, Richardton, Forest City, and LaLande (Beck *et al.* 1951) meteorites. The average nickel content of the iron phase is known for three of these, and by means of the iron-nickel phase diagram (Owen and Liu 1949)[2] it is possible to estimate the temperature at which these phases were produced. It is also possible to estimate roughly the relative proportions of the kamacite and taenite phases from the intensities of the X-ray diffraction patterns or the relative numbers of metal particles of the two kinds as viewed under the microscope. Studies of this kind have been much too sporadic,[3] but some conclusions can be drawn. The metal of Holbrook contains 16.5 per cent nickel (Foote 1912), and the ratio of kamacite to taenite is about 2 from X-ray diffraction patterns. This indicates that the separation of the phases was arrested at about 450° C. The metal of Forest City contains

[1] At the writer's suggestion, observations on Holbrook, Beardsley, and Forest City were made by Mrs. B. Nielson and Miss Ann Plettinger. Professor W. Zacharieson interpreted the X-ray diffraction patterns. C. W. Beck, R. G. Stevenson, and L. La Paz (1951) report these two phases in LaLande.

[2] Since the reference may not be readily available to many readers, the equilibrium percentages of nickel in the two phases are given below:

	T (° C)								
	300	350	400	450	500	550	600	700	800
Kamacite (α)	7.5	6.9	6.3	5.7	5.0	4.4	3.7	2.5	1.2
Taenite (γ)	56.0	48.5	41.5	34.3	27.5	22.2	17.3	9.4	3.8

[3] This has been due to lack of time on the part of the writer and to lack of sufficient other personnel in his laboratories.

Recently Kuiper (1954) has proposed that the solar system originated about 5 × 10^9 years ago, that insulated objects formed at this time, and that they melted some 5 × 10^8 years later because of radioactive heating by potassium, uranium, and thorium. It was assumed that after the melting process the radioactive elements became concentrated at the surfaces of these objects during a solidification process. Kuiper does not account for the conglomerate structures of the chondritic meteorites, which have not lost their A^{40} during the last 4.3 × 10^9 years.

Urey (1955) discussed radioactive heating but pointed out that the structures of chondrites would require a very vigorous breakup of the originally melted materials to form the chondrites which must have occurred some 4.5 × 10^9 years ago and that presumably this was part of the process of formation of the solar system. Radioactive heating then requires a long time, some 0.5–1.0 × 10^9 years, for the melting process *prior* to the time of active formation of the system. Thus Kuiper's time schedule does not meet the conditions unless some vigorous collisional process occurred some 0.5–1.0 × 10^9 years after the formation of the system. In order to avoid this unlikely event, Urey suggested that radioactive heating due to short-lived radioactive elements took place, e.g., Al^{26}.

Recently Donn and the writer (Donn and Urey 1956; Urey and Donn 1956) in two brief papers pointed out that chemical heating due to reactions of condensed free radicals or to thermodynamically unstable compounds with satisfied valencies derived from free radicals could be the source of explosions in comets and heating in a lunar-type object at the time of the origin of the solar system and that such heating melted the silicates and metal of the meteorites. This offers a very plausible explanation of the first of the problems mentioned above, but, as stated by them, it does not solve the problem of variable planetary densities. It is the purpose of this note to point out a solution to the second problem by an extension of their line of argument.

Urey and Donn (1956) assumed that objects of lunar mass grew by accretion of dust at low temperatures until considerable masses of silicates and free radicals, e.g., OH

taenite would indicate a temperature of 355° C, but this disagrees markedly with another analysis and is probably in error. Thus temperatures for the formation of these phases in the octahedrites run from 450° to 600° C and hence are in the same range as the more uncertain range estimated for the chondrites. If the analysis on Beaconfield is correct, a time comparable to the age of the solar system is required, and hence these phase separations occurred in the secondary objects. Otherwise they could have formed in times from 10^5 to 10^8 years and thus may have formed in the primary objects, as is necessarily true for the kamacite and taenite of the chondrites, Forest City, Beardsley, Richardton, LaLande, and Holbrook. Since diffusion coefficients decrease rapidly with increased pressure, high pressures would increase the required times very greatly. Also increased pressures cause a shift of the entire phase diagram to lower temperatures—by 200° C for a pressure of 10^5 atmospheres, according to Uhlig (1955). It is evident from Table 1 and the general effect of pressure that the kamacite and taenite of the iron meteorites could not have formed under such pressures during the whole of geologic time. Other iron meteorites require other conditions. The hexahedrites contain about 5.5 per cent nickel and consist of large crystals of kamacite, while the nickel-poor ataxites have the same composition but the crystals are very small. Perry (1944) believes that the hexahedrites crystallized at about 450° and the nickel-poor ataxites are reheated hexahedrites. This may have occurred in the secondary objects. Many points of the history of these meteorites are obscure, and probably several possible histories could be devised for them.

TABLE 1*

DIFFUSION TIME FOR NICKEL IN KAMACITE AND TAENITE

T (° C)		Kamacite ($l=0.2$ cm)	Taenite ($l=0.007$ cm)
300	D	1.5×10^{-22}	8.1×10^{-27}
	t	4.2×10^{12}	9.5×10^{13}
400	D	3.2×10^{-19}	5.5×10^{-23}
	t	2.0×10^{9}	1.4×10^{10}
450	D	6.5×10^{-18}	1.8×10^{-21}
	t	9.7×10^{7}	4.3×10^{8}
500	D	9.1×10^{-17}	3.8×10^{-20}
	t	6.4×10^{6}	2.1×10^{7}
600	D	7.2×10^{-15}	5.7×10^{-18}
	t	8.8×10^{4}	1.3×10^{5}

* Time in years; D in cm²/sec.

Diamonds have been observed in the Canyon Diablo and Magura octahedrites. So far as we know, diamonds cannot be produced except under fairly high temperatures and high pressures. Using thermodynamic data (Kelley 1949; Rossini, Wagman, Evans, Levine, and Jaffe 1952) and the densities of graphite (2.26 gm/cm³) and diamond (3.51 gm/cm³), the required minimum pressures at 1000° and 1200° K are 31000 and 37000 bars, respectively. The pressure at the center of the moon is 46000 bars, and hence we see that at least *one* of the primary or secondary objects was of lunar mass or greater. Since both Canyon Diablo and Magura are octahedrites and have well-developed Widmanstätten figures, we conclude, in view of the preceding paragraph, that they did not acquire both the kamacite and taenite of these figures and diamonds at the same time under the same conditions of temperature and pressure. Canyon Diablo contains some graphite and Magura large nodules of graphite, which appears to have crystallized at low pressures. They contain diamonds, which means that they were subsequently subjected to high pressures. Finally, Magura and some other irons contain graphite pseudomorphs of diamonds, so that they were again subjected to low pressures. All these processes occurred at least at moderate temperatures, for no crystallization of carbon into either graphite or diamonds will take place at ordinary temperatures (Farrington 1915). Diamonds and pseudomorphs of diamonds have been observed only in coarse octahedrites, with the exception of Toluca, which is a medium octahedrite. The rate of diffusion of carbon in iron is much greater than that of nickel (West 1950), and hence no problem of diffusion times exists.

The Urey and Donn model for chemical heating of the primary objects of lunar mass would supply the conditions for the formation of graphite at low pressures and diamond at high pressures, and radioactive heating in the secondary objects would provide conditions for the conversion of diamonds to graphite at low pressures. Under the last conditions the Widmanstätten figures could have been formed. However, the process is an involved one, and it can hardly be unique. The writer has devised other hypothetical processes, though none that seems as satisfactory as that mentioned.

Diamonds have been reported in the Carcote crystalline bronzite chondrite (von Sandberger 1889) but not from any other chondrite. Also they are reported in Novo Urei by Jerofejeff and Latschinoff, which was confirmed by Kunz (Jerofejeff and Latschinoff 1888; Kunz 1888). This is a rare type of achondrite, of which three are known. Neither of these has been dated by the K^{40}-A^{40} method, and both are not available to this laboratory. If diamonds are definitely shown to be present in chondrites of maximum age, the primary objects must have been of lunar mass or greater. In order that half the volume of an object of density 3.34 may be subject to a pressure of 37000 bars, it is necessary that its radius be 1.5 times the moon's radius.

4. The Urey-Donn heating mechanism by reactions of free radicals requires that the primary objects be of considerable size, in order that it may be an acceptable method for producing molten pools of silicates and metal. If the gravitational field is too low, the heated materials will be blown completely away from the object by the escaping gases, and, even if the field is sufficient to retain the gases and suspended liquids, they might be raised to high altitudes, be cooled, and the condensed phases would fall back as solids to the surface and thus supply no pools of liquids. The free radical heating process resembles physically and chemically a blast-furnace operation in which iron ore, limestone, and coke have gases passing through them and out at the top and liquid iron and melted silicates flow out at the bottom. A blast furnace would operate with great difficulty on the moon, for there would be a very great tendency for all products to leave at the top of the apparatus. We emphasize the qualitative problem but can draw no quantitative conclusions.

The superficial heating of objects would not provide any method for the formation of diamonds, since no high-pressure regions would be established.

Radioactive heating in objects formed some 10^9 years before the history under discussion could have supplied the melted iron and silicates and the kamacite and taenite if the primary objects were of asteroidal size. However, they could not have done this if they were large, because of the time required for cooling, as Urey and Donn point out; thus diamonds could not have formed in the primary objects if melting was due to radioactive heating either by potassium, uranium, and thorium or by short-lived nuclides.

The achondritic meteorites have less potassium and sodium than the chondrites. This is particularly striking in the case of those achondrites having a chemical composition similar to basalt, except that the concentrations of alkalies are much too low. (The mineral compositions differ from those of basalts, and hence their histories are not the same in all details.) The Pasamonte meteorite illustrates the similarity in chemical composition very well (see Table 2). The Nuevo Laredo meteorite belongs to the

Howardites, as does Pasamonte. Uranium and barium have higher concentrations and the alkalies lower concentrations in this meteorite than in the chondrites (Turkevich, Reed, and Hamaguchi 1956). Thus the differences shown in Table 2 extend to the minor constituents. The free-radical heating method would account for these facts; for partial melting of the primitive silicates should produce a basaltic liquid and the escape of gases should volatilize the alkalies and not the other constituents, as is well known from laboratory experience on melting silicates. The volatilized alkalies and other volatile elements would condense as dust and fall back to the surface, but the silicate melts would be deficient in alkalies, as is observed. The Urey mechanism of heating by the fall of these objects through gases at high velocity would supply superficial heating and volatilization of the alkalies from silicates. In this case the materials at the center of the object would not be heated and fractionated in this way; these materials supplied the higher concentrations of these elements in the chondrites. There is no evident process by which radioactive heating could have produced the loss of alkalies. On the basis of this argument, the achondrites generally are relics of the primary objects and do not owe their *chemical composition* to reheating in the secondary objects, even though such reheating may account for the loss of A^{40} and hence lower observed ages for some of them. (Both the Pasamonte and the Frankfort K^{40}-A^{40} ages are 3.3–3.5 $\times 10^9$ years [Geiss and Hess, unpublished], and an estimate of the radioactive heating in highly insulated objects indicates a 500° or 600° C rise in temperature quite sufficient to remove argon during the times considered.) Schumacher's Rb^{89}-Sr^{89} age of 4.5 $\times 10^9$ years for Pasamonte shows that the removal of rubidium occurred very early and supports the view that this took place in the primary objects.

TABLE 2*

COMPOSITION OF TERRESTRIAL BASALTS, THE PASAMONTE METEORITE, AND THE SILICATES OF THE CHONDRITES (IN PERCENTAGES)

	Pasamonte	Average Basalts	Average Silicate of Chondrites
SiO_2	48.20	49.06	47.04
MgO	6.47	6.17	29.48
FeO	17.04	6.37	15.40
Fe_2O_3	0	5.38	0.00
Al_2O_3	13.91	15.70	3.09
CaO	10.24	8.95	2.41
Metal	2.64	0.00	....
FeS	0.19	0.13	....
Na_2O	0.54	3.11	1.11
K_2O	0.066	1.52	0.122
Rb_2O	0.63 p.p.m.	70 p.p.m.	5.3 p.p.m.

* The average of the basalts is taken from Rankama and Sahama (1950), except for the rubidium, which is taken as 1/200 of the potassium, since Ahrens, Pinson, and Kearns (1952) have established by recent work that this ratio is nearly constant. The Pasamonte analysis is by W. Foshag (1938) except for the sodium and potassium analyses, which are by Edwards (1955), and the rubidium analysis, which is by Schumacher (1956). The analysis of the silicate phases of chondrites is taken from Urey and Craig (1953), except that the sodium and potassium values are from Edwards (1955) and that rubidium is a single value for the Forest City meteorite from Schumacher (1956).

Our conclusions from this discussion are as follows: Both the primary and secondary objects existed, and either one group or the other or both were sufficiently massive to produce diamonds. The primary objects collected, were heated to above 1500° C, and cooled to 450° or 600° C. After remaining at this temperature for some 10^8 years, they were broken up mostly into fine particles, though some of the fragments were fairly large and supplied fragments like the achondrites and iron meteorites. These fragments were accumulated into the secondary objects within a time of the order of 10^8 years. These secondary objects have collided with each other from time to time during the last 4.5×10^9 years, and the fragments are the meteorites. Arguments that the primary objects were of lunar mass are inconclusive; but, independently of the question of the time and place at which the diamonds were formed, the arguments indicate that the primary objects were of asteroidal dimensions or larger.

APPLICATION TO THE ORIGIN OF THE SOLAR SYSTEM

The foregoing outline of events leads to an interesting conclusion. First, a quiet period of accumulation of the primary objects and a resting period of considerable time are required. Second, a period of violent collisions must have occurred. Third, a period of reaccumulation into asteroidal bodies is required. If these events occurred under the same physical conditions during a short period of time, then it would appear that the meteorites are the result of a series of events of low probability. It is more reasonable to assume that these processes occurred under different physical conditions.

It is the purpose of this paper to explore a possible course of events in which it is assumed that the intense collisional process occurred during the formation of the solar system and that these collisions were an important and not merely an incidental part of the physical processes. In this case the accumulation of the primary objects preceded the active and energetic processes involved in the formation of the system. This reasoning indicates that these objects may have accumulated in the primitive dust cloud before the sun was formed or that they were captured by the sun from such a dust cloud. Any preceding condition consistent with the accumulation of these objects and the formation of their characteristic minerals would be satisfactory to the present discussion. The chemical heating process would supply heat regardless of the presence of a star or of adiabatically compressed gases, which are the usually assumed sources of heat.

POSTULATED MODEL FOR THE ORIGIN OF THE SOLAR SYSTEM

In this paper it is suggested that objects of considerable size and mass accumulated in a dust cloud at low temperatures. Intermittent chemical heating may have produced molten silicate and metal phases. After some period of time, millions or tens of millions of years, these objects fell rapidly toward a gravitation center, and the sun was formed with a disk of residual gas and these objects. Melting of the silicate and metallic materials may have occurred during this process. In this process intense collisions occurred which reduced the solid material to fragments varying from micron sizes and smaller to the sizes of the materials of the chondritic meteorites and iron meteorites. The gas and dust were dissipated from the disk by solar light-pressure and turbulent gases, and some of the solid material was removed by the Poynting-Robertson effect. The planets and asteroids accumulated during this time. Protoplanets in the sense of masses of gas and solids of solar composition did not occur, at least in the case of the terrestrial and minor planets, or, if protoplanets were present at all, they did not form until the permanent gases were removed and the fractionation of the silicate and metallic phases was complete, and hence they did not have the mean solar composition. The satellite systems of the major planets were formed by analogous processes.

The problem of the accumulation of large objects in interstellar dust clouds is a difficult one for which no mathematical discussions are available. We know that the clouds as we observe them today contain micron-sized or smaller particles in great numbers (Platt 1956). Also comets appear to be objects which formed in regions of very low densities of matter, so that some accumulation of solid matter does occur even under these conditions. Small solid objects in a gas present a very unstable situation, since these objects will fall toward a region of higher density and convert their kinetic and potential energy into heat. Such processes are thermodynamically irreversible. Passing stars must concentrate dust in their wakes, and such concentrations of gas and dust will fall toward any other high-density centers. It is easily seen that these processes are very complicated. However, it is evident that the accumulation will be a rapidly accelerating process as any object grows, and, if objects of lunar mass once were formed, rapid sweeping up of smaller objects should occur.

Also, a gas mass containing lunar-sized objects and probably more of smaller mass would be highly unstable, because the objects would fall rapidly toward any region of increased density. The smaller objects, in particular, would be decelerated by the gas and would increase the gravitational field, thus increasing the movement of gases toward such a center. In fact, such effects might produce an almost implosive origin of stars. Such objects, not subject to the hydrodynamic behavior of gases, would substantially stabilize the process of star formation. Altogether, such effects might make certain features of the formation of stars more understandable, as, for example, the formation of the O stars within quiet clouds, as discussed by Oort and Spitzer (1955) and Strömgren (1954). The "non-volatile" fraction of solar matter could supply some 10^5 moons. Some of the gas and solid objects would not become part of the sun, and it can be reasonably postulated that the gases formed a gaseous-disk nebula in the plane of the ecliptic, as had been assumed previously, and the primary objects which first plunged through this collided with one another and finally moved within the disk. Indeed, the debris would accumulate fairly close to the median plane if the gases were not too turbulent. While the mass of the earth distributed in the neighborhood of the earth's orbit within a ring 0.4 A.U. wide and 0.15 A.U. thick would supply a density of solid particles of only some 5×10^{-12} gm/cm^3, this same material concentrated in a plane amounts to some 10 gm/cm^2, and the total solid material in this region may have been many times the present earth mass at the time that we are considering. This concentrating effect would promote many collisions. The chondritic meteorites testify definitely and conclusively to the existence of such collisional processes during a period about 4.5×10^9 years ago.

The meteorites are assumed to be members of the asteroidal belt of objects. The total mass of the asteroids is estimated as $0.002\ M_{\oplus}$, while the mass of the moon is $0.0123 M_{\oplus}$. The history we are outlining requires at least two large objects, in order that there may be at least one effective collision and thus about twelve times the mass now present in this region. Again the total material at the time being considered may have been many times this amount. However, the varying densities of the planets (Urey 1952) and the existence of two prominent groups of meteorites with different iron-to-silicate ratios (Urey and Craig 1953) require that some material be lost and that this loss result in variable proportions of the more and less dense fractions of "non-volatile" constituents. This is precisely what must be expected on the basis of the present model. Assuming that the sun acquired its present luminosity at the period under consideration or at any previous time, several effects would dissipate the solar nebula, namely: (1) gases and very small-sized dust would be lost from the disk-shaped solar nebula because of radiation pressure driving them away from the sun; (2) somewhat larger particles would move toward the sun because of the Poynting-Robertson effect; and (3) particles would be lost by the dissipation of the solar nebula through the mechanism of loss of turbulent gases from the system, as von Weizsäcker and ter Haar (1946) have maintained. Part of the gases and solids would move into the sun and part to greater distances and probably some to an infinite distance. All these processes favor the removal of the smaller and lower-density particles. In collisions the weaker and more easily shattered silicates, as compared to metallic iron-nickel, would be broken into smaller particles; hence these would be removed preferentially, leaving residues enriched in metallic iron-nickel. The solids approaching the sun would be volatilized and at least partially driven away from the sun again, so that the total material entering the sun may have been small. In this case no especially high-temperature sun is required to produce this fractionation, though a somewhat more luminous sun would accelerate the process. Thus the second problem mentioned in the opening paragraph of this paper is solved quite naturally by this model.

The rate at which objects move toward the sun because of the Poynting-Robertson effect is proportional to the light-intensity and inversely proportional to the product of the density and radius of the particle (Wyatt and Whipple 1950). Elementary calculations show that the energy required for the removal of solid objects by this effect is fairly large. Thus the energy received by a spherical black body of radius s and distance a from the sun is

$$\frac{L_{\odot}}{4}\frac{s^2}{a^2}\,dt\,,$$

where $L_{\odot}$ is the energy per second radiated by the sun. Substituting for dt from the equation for the Poynting-Robertson effect for a circular orbit, namely,

$$dt = -\frac{8}{3L_{\odot}}\,\pi c^2 s \rho a d a\,,$$

dividing by $\frac{4}{3}\pi\rho s^3$, and integrating gives $c^2/2$ in a_0/a for the energy per gram. Using 3 A.U. and 10^6 km as reasonable limits for a_0 and a gives 2.7×10^{21} ergs/gm. This is a very large energy requirement, which could be supplied only by the sun during times much greater than 10^9 years if masses of the order of the terrestrial mass or greater are to be removed and if only the energy from a narrow region of the sun is available. The Poynting-Robertson effect would furnish only an auxiliary mechanism for removal of solids.

The removal of dust particles by light-pressure under the conditions being considered, namely, mixtures of dust and gas, is a most involved process. Calculations based on simple models would be of most doubtful value. This is even more true for particle radiation, since we know so little about the mechanism by which high-velocity particles are produced by the present sun. Bierman (1951) estimates concentrations of 10^3–10^5 protons and electrons per cubic centimeter near the earth and velocities of 10^8 cm/sec. The high concentrations exist for only short periods of time. Using the lower number, the pressure produced by stopping these particles, ρv^2, is 1.6×10^{-5} dyne/cm², as compared to a solar light-pressure of 4.5×10^{-5} dyne/cm².

High-velocity particles are capable of accelerating individual atoms of high atomic weight to high velocities, though the probability of effective collisions of this kind is very small. Bierman finds that the material of comet tails is accelerated by particle radiation instead of light-pressure, and the dissipation of comet tails from a region of a low local gravitational field is very similar to the process considered in this paper for the dissipation of the solar nebula. However, to the extent that such dissipative processes were effective, they would carry away the smaller and lower-density silicate particles to a greater degree than the higher-density metallic particles.

Small dust particles would move with any hydrodynamic movement of the gas. The Reynolds' number is defined as $\rho v d/\eta$, where ρ is the density; v the velocity of flow, which is approximately the orbital velocity; d an appropriate linear dimension; and η the viscosity; the gas flow becomes turbulent when this number exceeds 100,000. With v equal to 3×10^6, d equal to 1 A.U. or 1.5×10^{13} cm, and η equal to 10^{-4} poise, the critical density is 2.5×10^{-19} gm/cm³, and hence, until this density is reached, turbulent flow of gas will result. Ter Haar (1946) has discussed the turbulent dissipation of the solar nebula and estimates the time required as 1000 years, which, as he observes, seems to be very much too low. It should be noted that the presence of solid objects of such mass that they would not move with the gas would decrease the value of d by many orders of magnitude, and hence the loss of gas would not be so complete as estimated above. Ter Haar remarks that "the condensation into planets started at a time when there was a strong interaction between the solar envelope and the surrounding interstellar gas, so that the dissipation process was counteracted by a replenishing of matter from the surrounding interstellar medium." Although we tend to describe these processes in successive stages, the actual course of events was continuous, and hence dissipation began before the solar nebula was formed. Chandrasekhar (1946) shows that small dust particles will move with turbulent gases and thus be carried with high velocity to large objects not moving with the gas. He estimates that the time of accretion of planetary bodies may be some 10^7 years. Chandrasekhar's mechanism might apply to the accumulation of comets and the primary objects discussed here. For our present purposes, we note that the turbulent gases would also carry off the particles of lower density and smaller size and hence would remove silicate rather than metallic particles as the gas was moved toward the sun or to infinity, as postulated in the discussions on the turbulent gas nebula.

Many factors might have occurred which would influence the rate of removal of debris from the solar-disk nebula, such as (1) the intensity of sunlight as influenced by the luminosity of the sun and absorption by intervening materials, (2) the size of the particles and their densities, and (3) the condensation of water or other low-density substances on the more dense particles. Such condensation would have occurred at great distances from the sun, and the density of such condensed materials may have been very low indeed. Also the planets were presumably growing, and a competition among these processes must have taken place. If the suggestion of this paper is correct, the distribution of mass among the planets and the asteroidal belt very probably was influenced in an important way by these dissipative processes.

Maxwell discussed the stability of the rings of Saturn in a classical paper. He considered no forces which would degrade energy to heat and found that the rings would be stable. If gas were present or if the particles contained metal and thus were magnetic and conductors and a solar magnetic field existed, frictional forces would be present, and under these conditions the rings would probably not be stable and the particles would eventually touch one another. Within the Roche limit they would separate again unless the physical strength of the body was sufficient to prevent disruption by tidal forces. Thus the rings of Saturn would be stable, i.e., the particles would not coalesce, but similar rings outside the Roche limit would most probably agglomerate. It is often suggested that a satellite or satellites moved within the Roche limit and broke up to form the rings. Is it not possible that the satellites outside this limit accumulated from fine material and that the rings represent the more primitive situation? It is this latter possibility which is being considered here. The carbonaceous chondrites contain appreciable quantities of water, and collisions between such objects would produce gases. Thus a continuous production of gases and their removal would provide frictional forces and at the same time sweep out the inert gases from the region of the terrestrial planets.

For a number of years the writer has been troubled by difficulties in securing a satisfactory model for the problems discussed in this paper using the Kuiper (1951) protoplanet model. The problems briefly are as follows: (1) the removal of the inert gases, especially xenon, from the earth requires that gases be removed while the mass of the earth was distributed over a large volume and thus solid masses must have been distributed in this way within the protoplanet; (2) in order to secure a high temperature so that some of the silicates were volatilized, namely, some 2500° K at the center of the protoplanet, the ratio of mass to radius must have been one-quarter the present ratio for the earth, as is easily calculated from Emden's tables for a sphere of polytropic index 2.5, i.e., hydrogen gas; (3) the escape energy for this sphere is one-quarter that of the earth, and it is not evident that there is any feasible way for removing xenon from its surface, while the removal of silicate dust presents an even greater problem; and (4) the process must have been accomplished quickly in order that the high temperatures did not completely volatilize the solid planetesimals within which the more volatile elements were assumed to have been preserved (Urey 1954). It is difficult to prove that some possible combination of events could not have met these conditions. Perhaps gases and solids were lost in some way because of rotation, but surely no convincing discussion has been presented. A high-temperature sun of great luminosity for a brief period of time due to the early thermonuclear reaction of deuterium or helium of atomic weight 3 has often been thought of by the writer as a possible solution to these problems. The writer has found it necessary to retain the protoplanet model because no other source of high temperature for producing the minerals of the meteorites had been suggested, even though this model had these serious difficulties. However, the model suggested in this paper does not present these difficult problems, since it postulates the removal of gas and solids before any protoplanet structure was formed.

It has been evident to all students from Galileo to the present that the satellite systems of the major planets are very similar in structure to the solar system and that it seems reasonable to expect that a similar mechanism of formation should apply. Jeans (1929) says: "Each of these small systems is so exact a replica in miniature of the solar system that no suggested origin for the main system can be accepted unless it can account equally for the smaller planetary systems; any hypothesis which assigned different origins to the main system and the subsystems would be condemned by its own artificiality." Yet he proposes a gravitational instability of a gaseous medium as the mechanism for the formation of the planets and concludes that the asteroids and the satellites of Saturn must have been liquid or solid from birth; thus he used quite different mechanisms for the solar and satellite systems. The protoplanet hypothesis of Kuiper cannot be applied to these small satellites of the major planets because their masses are much too small to retain any gaseous envelope and hence their nearly circular orbits and the regular spacing cannot have been produced by a protosatellite mechanism. On the other hand, the writer sees no compelling objection at the present time to the possibility of applying the ideas presented in this paper to the planets and asteroids as well as to the satellites of the major planets.

Herbig (1954) has made an intensive study of the T Tauri stars in recent years and has pointed out that some of these stars are probably associated physically with the ζ Persei cluster of B-type stars which Blaauw (1952) has shown are not over 1.3×10^6 years old. These T Tauri stars are G to M dwarf-type stars imbedded in dust clouds and may well be the type of star being considered here. If this is the case, we are witnessing the dispersal of the solar nebulae of these stars. The bright-line spectra extend to considerable distances from these stars and show the bright lines of H I, Ca II, O II, and S II, indicating that some of the "non-volatile" elements, such as calcium, are dispersed as atoms and at least not entirely as dust particles.

The present suggested events for the origin of the solar system are not satisfactory in a number of ways. This model does not explain the presence of only one planet at each distance from the sun. This is the basis of the protoplanet model, but that model does not explain the spacings of the satellite systems. Also there is no satisfactory theory for the accumulation of either small or large objects in interstellar dust clouds, though the mechanisms involving turbulent gases as discussed by Chandrasekhar (1946) might be applicable. Also the turbulent gas mechanisms as oulined for the solar nebula by ter Haar and von Weizsäcker may furnish adequate mechanisms for the accumulation of satellites, asteroids, and planets.

Kuiper (1953) has proposed a mechanism for the accumulation of asteroids and satellites of the major planets other than the protoplanet mechanism. First, he assumes that objects some 50 km in radius accumulated by molecular condensation of silicate gas. (His only specification is a molecular weight of 50.) Then these objects accumulated, by some mechanism not further described, into objects of asteroidal dimensions. The first part of this proposal was first presented by Hoyle (1947). The condensation of supersaturated silicate gas on a few limited centers, some ten perhaps or even a hundred in the asteroidal belt, during 10^7 years is an impossible physical process. Supersaturated gases, except under very special conditions, condense to clouds of micron-sized particles in a fraction of a second. In no known way could supersaturated gases persist for long periods of time, especially in the presence of radioactive substances at the densities assumed. Dust is observed in interstellar space even at much lower densities. What we need is a mechanism for the accumulation of micron-sized dust particles into the primary objects and of the fragments present in the chrondrites into the secondary objects.

Schmidt (1944) has postulated solid objects as part of his theory for the formation of the solar system, though the theory of capture of objects by the sun was based on incorrect celestial mechanics. His formula for the accumulation of the planets has recently been derived again by Safranov (1954), who assumes that solid dust particles would behave like a gas, with the particles moving with random mean velocities of 10^5 cm/sec. Micron-sized silicate particles moving with such velocities would require the temperature to be 10^{14} °K. This makes this theory quite unacceptable. Yet the school of O. J. Schmidt has quite independently maintained for years that solids were an important part of the early history of the solar system, and with this general point of view this writer agrees. He has been aware of these suggestions, and yet, aside from the fundamental difficulties outlined above, he has not accepted them because they not only fail to account in any way for the properties of the meteorites but also in no way attempt to do so. Chemical substances and minerals have much more detailed properties than a mean molecular weight or a mean density, and these properties are often very informative and also very limiting as to postulates which can be made concerning their origins. I can think of no possible way to modify these suggestions to account for the properties of the meteorites except by a completely new approach to the problem, based on observational data, such as is attempted in this paper, rather than on simple theoretical calculations.

CONCLUSIONS

A series of events during the origin of the solar system has been postulated which accounts for at least some of the characteristics of meteorites and for the varying densities of the planets. It is suggested that objects of about asteroidal or lunar mass accumulated early in the history of the solar system. Two possible heating mechanisms are considered by which the minerals and metal phases of meteorites were produced, namely, chemical heating by free-radical reactions or heating by the fall of objects through gases. These primary objects were broken up in collisions and partially reaccumulated into secondary objects, probably of a class with the present asteroids. During the process of breakup and reaccumulation, fractionation of the silicate and metal phases occurred, with a preferential loss of silicate phases in varying degrees. This variable loss accounts for the variation in densities of the planets. The reaccumulation process probably was part of the general process of planet formation.

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REFERENCES

Ahrens, L. H., Pinson, W. H., and Kearns, M. M. 1952, *Geochim. et cosmochim. acta*, **2**, 229.
Allen, D. W., and Jacobs, J. A. 1956, *Geochim. et cosmochim. acta*, **9**, 256–272, esp. 270.
Beck, C. W., Stevenson, R. G., and LaPaz, L. 1951, *Pop. Astr.*, **59**, 88.
Bierman, L. 1951, *Zs. f. Ap.*, **29**, 274.
Blaauw, A. 1952, *B.A.N.*, **11**, 405.

Chandrasekhar, S. 1946, *Rev. Mod. Phys.*, **18**, 94.

Donn, B., and Urey, H. C. 1956, *Ap. J.*, **123**, 339.

Edwards, G. 1955, *Geochim. et cosmochim. acta*, **8**, 285.

Edwards, G., and Urey, H. C. 1955, *Geochim. et cosmochim. acta*, **7**, 154.

Eucken, A. 1944, *Nachr. Akad. d. Wiss., Göttingen, Math.-phys. Kl.*, No. 1, pp. 8, 9.

Farrington, O. C. 1915, *Meteorites* (Chicago: The author).

Foote, W. M. 1912, *Am. J. Sci.*, **34**, 437.

Foshag, W. F. 1938, *Am. J. Sci.*, **35**, 374.

Geiss, J. 1956, unpublished data.

Gerling, E. K., and Rik, K. G. 1955, *Doklady Akad. Nauk, U.S.S.R.*, **101**, 433.

Haar, D. ter, 1950, *Ap. J.*, **111**, 179.

Henderson, E. P., and Perry, S. H. 1954, *Geochim. et cosmochim. acta*, **6**, 221–241.

Herbig, G. H. 1954, *Pub. A.S.P.*, **66**, 19; *Ap. J.*, **119**, 483.

Hoyle, F. 1947, *M.N.*, **106**, 406.

Jeans, J. 1949, *Astronomy and Cosmogony* (Cambridge: At the University Press), p. 406.

Jerofejeff, M., and Latschinoff, P. 1888, *Verk. Russ. Min. Gesellsch. St. Petersburg*, **24**, 263.

Kelley, K. K. 1949, *Contributions to Data on Theoretical Metallurgy* (Bur. of Mines Bull. 476).

Kuiper, G. P. 1951, *Astrophysics*, ed. J. A. Hynek (New York: McGraw-Hill Book Co.), chap. viii.

———. 1953, *Proc. Nat. Acad. Sci.*, **39**, 1159.

———. 1954, *ibid.*, **40**, 1101.

Kunz, G. F. 1888, *Science*, **11**, 118.

———. 1890, *Am. J. Sci.*, **40**, 318.

Oort, J. H., and Spitzer, L., Jr. 1955, *Ap. J.*, **121**, 6.

Owen, E. A., and Liu, Y. H. 1949, *J. Iron and Steel Inst.*, **163**, 132–137.

Patterson, C. C. 1955, *Geochim. et cosmochim. acta*, **7**, 151. This work was first presented at a conference on the abundances of elements at Williams Bay, Wisconsin, September, 1953.

Perry, S. H. 1944, U.S. Nat. Museum Bull. 184.

Platt, J. R. 1956, *Ap. J.*, **123**, 486.

Prior, G. T., and Hey, M. H. 1953, *Catalogue of Meteorites* (London: British Museum).

Rankama, K., and Sahama, Th. G. 1950, *Geochemistry* (Chicago: University of Chicago Press), p. 159.

Rossini, F. D., Wagman, R. D., Evans, W. H., Levine, S., and Jaffe, I. 1952, *Selected Values of Chemical Thermodynamic Properties* (Nat. Bur. Standards Circ. 500).

Safranov, W. S. 1954, *Astr. J. U.S.S.R.*, **31**, 499.

Sandberger, F. von 1889, *Neues Jahrb. Min.*, **2**, 173.

Schmidt, O. J. 1944, *Rept. Acad. Sci. U.S.S.R.*, **45**, 245–249, and a number of later papers. See "Les Particles solides dans les astres," *6th Liège Colloquim, Mem. Soc. Roy. des Sci. d'Liège*, 4th Ser., **15**, 638.

Schumacher, E. 1956, *Helvet. chim. acta*, **39**, 531, 538; *Zs. f. Naturforsch.*, **11a**, 206.

Smith, W. Campbell. 1950, *Adv. Sci.*, **7**, 143–153.

Strömgren, B. 1954, *Mem. Soc. Roy. des Sci. Liège*, 4th Ser., **15**, 624.

Turkevich, A., Reed, G., and Hamaguchi, H. 1956, private communication.

Uhlig, H. H. 1954, *Geochim. et cosmochim. acta*, **6**, 282.

———. 1955, *ibid.*, **7**, 34.

Urey, H. C. 1952, *The Planets* (New Haven: Yale University Press).

———. 1954, *Ap. J. Suppl.*, **1**, 147–173.

Urey, H. C., and Craig, H. 1953, *Geochim. et cosmochim. acta*, **4**, 36–82.

Urey, H. C., and Donn, B. 1956, *Ap. J.*, **124**, 307.

Wasserburg, J. G., and Hayden, R. J. 1955, *Phys. Rev.*, **97**, 86.

Weizsäcker, C. F. von. 1944, *Zs. f. Ap.*, **22**, 319.

West, C. A. 1950, *Phys. Rev.*, **79**, 601.

Wyatt, S. P., Jr., and Whipple, F. L. 1950, *Ap. J.*, **111**, 134.