

by the homogeneous behavior of native and enzymatically liberated maple lignins in electrophoresis, as contrasted with the indication of a secondary component in both these lignins by the paper-chromatographic technique.

As a result of this study, lignins should be regarded as mixtures of components, all possessing similar structures but with the possibility of certain chemical differences, as discussed above. It is for such mixtures of substances which may differ both in structure and in molecular size that Staudinger introduced the term *Gruppenstoffe*.¹²

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*THE COSMIC ABUNDANCES OF POTASSIUM, URANIUM, AND
THORIUM AND THE HEAT BALANCES OF THE EARTH,
THE MOON, AND MARS**

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In a discussion of the abundances of the elements the writer¹ did not select values for the abundances of uranium and thorium because of the great variability in the older data, but especially because the more recent values for uranium and thorium contents of meteoritic material seemed to be much too high to permit an understanding of the heat balances of the earth and moon. Chackett, Golden, Mercer, Paneth, and Reasbeck² found 0.106 and 0.335 p.p.m. for the mean content of uranium and thorium in the Beddgelert meteorite, and Davis³ found somewhat smaller values in achondrites. Such values would require that "much more heat has been generated in the moon and earth than seems likely to me, and I have been unable to think of any reasonable process to account for less uranium in the moon and earth than in the meteorites."¹ The difficulties represented by the chemical homogeneity of Mars⁴ should have been included, for it seems most probable that

Mars would have melted during geologic time if it had contained the reported amounts of these elements and hence would have formed a core, and this appears not to be the case on the basis of present data. Since this paper was written, many other data have accumulated which indicate that the general level of the uranium abundances in the Beddgelert meteorite is indeed representative of the chondritic meteorites. The amounts of uranium in the iron meteorites as reported by Dalton, Golden, Martin, Mercer, and Thompson⁵ and by Davis³ are of the order of a few per cent of this value for Beddgelert. Since uranium is very electropositive,⁶ the element is probably not dissolved in the metal but occurs in inclusions which are known to be present in these objects. A few per cent of such inclusions seems probable, but some 10 or 20 per cent, as would be required if the abundance of uranium were one-tenth that reported for Beddgelert, i.e., about that reported for the Modoc meteorite by Patterson *et al.*,⁷ 1.1×10^{-8} gm/gm, would be an impossible assumption. Either uranium is dissolved by metallic iron for reasons that are not understandable on the basis of its chemical properties, or the analytical data on the iron meteorites are incorrect for reasons that are far from obvious, or some material containing uranium in about the concentrations indicated for Beddgelert are occluded in iron meteorites to the extent of a few per cent. Recent results of Patterson⁸ on the uranium and lead contents of several chondritic meteorites indicate that their uranium contents are about the same as that secured for Beddgelert. It seems that we must accept the conclusion that there is much more uranium and thorium in these meteorites than appeared to be the case on the basis of the data reported for Modoc.

The Heat Balance of the Earth.—The rates of heat generation by the radioactive elements have been calculated previously, but because of the improvement in data⁹ it is possible to recalculate these values. By adding the energies of transitions, correcting the alpha-particle energies for recoil, and using 35 per cent of the maximum beta-ray energies as the non-neutrino energy, values of the heat energy per gram for U²³⁸, U²³⁵, and Th²³² have been calculated and are given in Table 1. There

TABLE 1
HEAT ENERGY CONSTANTS OF K, U, AND Th

NUCLIDE	HEAT ENERGY (MEV)	HEAT ENERGY (ERGS/GM $\times 10^{-17}$)	E (CAL/GM $\times 10^{-9}$)	dE/dt	
				Ergs/Gm Sec $\times 10^{-7}$	Cal/Gm Yr
K ⁴⁰	0.71	0.171	0.410	0.935	0.223
Th ²³²	39.9	1.66	3.96	0.828	0.198
U ²³⁵	44.2	1.82	4.34	17.64	4.21
U ²³⁸	47.1	1.91	4.56	2.935	0.701

may be some doubt in regard to the choice of some data. In the case of Ac²²⁸ the energy was calculated as that of a beta ray of 1.7 mev plus a gamma ray of 0.80 mev; for Pb²¹² the energy was taken as a beta ray of 0.331 mev and a gamma ray of 0.0238 mev; for the Bi²¹² to Pb²⁰⁸ transitions a total heat energy of 9.82 mev is used, which is the heat energy for the path Bi²¹² \rightarrow Tl²⁰⁸ \rightarrow Pb²⁰⁸ and which is a reasonable estimate for the heat energy by the more involved Bi²¹² \rightarrow Po²¹² \rightarrow Pb²⁰⁸ path. The energies for other transitions seem to be obvious. The results are probably good within a few per cent. Bullard¹⁰ secured 43.7, 47.6, and 40.1 mev for U²³⁵, U²³⁸, and Th²³², respectively, and these values are not greatly different from those used here. Birch¹¹ secures almost identical values for U²³⁸ and Th²³² but

gives a 1-mev larger value for U^{235} . The mean energy for K^{40} has been reviewed by Birch,¹² who secures 0.708 mev. It seems difficult to improve on this value, even though recent evidence indicates a different branching ratio.¹³ The half-lives, λ , are taken as K^{40} , 1.27×10^9 ; Th^{232} , 13.9×10^9 ; U^{235} , 7.13×10^8 ; and U^{238} , 4.51×10^9 , all in years. The energy released per gram and per second given in the last two columns is then calculated from the equation $dE/dt = E(0.693/\lambda)$, where E is the total heat energy per gram and dE/dt the rate of generation of heat energy. Then energies are given both in ergs per second and in calories per year.

The abundances of the important radioactive elements in meteorites are not well known, but Paneth's value for the Beddgelert meteorite is consistent with Patterson's values, and for the present calculations we shall use 0.106 and 0.335 p.p.m. for uranium and thorium, respectively, as the mean for the meteorites. Arguments have been given previously that the chondrites represent an average value for meteoritic abundances, and hence Davis' values for the achondrites are not averaged with the Beddgelert chondrite. For potassium we shall use 880 p.p.m., which is the average given by Edwards and Urey¹⁴ and is closely the same as that of Ahrens, Pinson, and Kearns.¹⁵ The former authors have investigated the potassium content of the carbonaceous chondrites and found it somewhat less than that of the chondrites and more variable. These objects appear to be chondritic material of the high iron group¹⁶ which has been subjected to the action of water, and we do not know to what extent they should be included in a proper average. The potassium content of the achondrites is variable, and again it is difficult to estimate what their contribution to average material should be. We shall take Nier's value of 0.000119 for the fraction of K^{40} in potassium at the present time.

Table 2 gives values for the present instantaneous rate of heat generation and for the heat generated during the last 5×10^8 , 4.5×10^9 , 5.0×10^9 , and 5.5×10^9

TABLE 2
HEAT PRODUCTION IN CHONDRITIC METEORITES

NUCLIDE	dE/dt AT PRESENT (ERGS/YR GM OF METEORITE)	TOTAL E IN JOULES PER GRAM OF CHONDRITIC METEORITE IN LAST			
		5×10^8 Years	4.5×10^9 Years	5×10^9 Years	5.5×10^9 Years
K^{40}	0.98	56	1,910	2,570	3,430
Th^{232}	2.77	139	1,400	1,570	1,750
U^{235}	0.14	9	1,090	1,770	2,890
U^{238}	3.11	162	2,020	2,370	2,690
Total	7.00	366	6,420	8,280	10,760

years in average chondritic meteoritic matter for each of the four important nuclides K^{40} , Th^{232} , U^{235} , and U^{238} . The heat of fusion of such material is about 400 joules per gram. If the earth's mantle was made of this material and if it was at the melting point at the beginning, enough heat has been generated to melt nearly the entire mantle during the last 5×10^8 years. The rate of heat loss from the earth is estimated to be 9×10^{27} ergs per year,¹⁷ and this value is believed to be accurate within 20 per cent. In 5×10^8 years this would amount to 110 joules per gram, taking the mass of the earth's mantle as 4.1×10^{27} gm. Still, there should have been enough heat to melt some 65 per cent of the earth's mantle. The large values for the heat generated during the last 4.5×10^9 years make it very probable that it would have been at the melting point at the beginning of this

period, and in fact melting should have occurred early in the earth's history, and the mantle should have remained at the melting point or above through all geologic time. It is impossible to believe that this has been true. We must conclude that the earth's mantle does not contain as much of these radioactive elements as do the meteorites. Since the writer believes that serious difficulties will arise in understanding the structures of the moon and of Mars unless the concentrations of these elements in the planets are less than in the meteorites, we must explore the possibility that abundances of these elements in the meteorites do not represent the cosmic abundances but that these elements have been concentrated in the meteorites. The alternative is that these elements have been depleted in the earth, the moon, and Mars. This possibility will be explored later in this paper.

At the Rome meeting of the U.G.G.I. (September, 1954) Dr. Roger Revelle suggested to me that the rate of heat loss of the earth is now and perhaps always has been equal to the rate of generation of heat in the earth. He suggested that a rise in temperature of the mantle will cause more rapid convections and a more rapid dissipation of heat, and a fall in temperature will produce the opposite effects until equilibrium is attained again. The assumption of near equality of heat loss and heat generation is made implicitly by Bullard¹⁷ and by Birch,¹¹ though they both believe that the earth is cooling and that the heat loss exceeds the rate of heat generation. If the temperature of the earth is falling with time, then the rate of loss will be higher than the instantaneous rate of heat production, and, if it is rising, the reverse is true. This statement of equality of rate of generation and loss of heat is accepted as true for the purposes of this paper, even though the writer favors a lower concentration of radioactive elements in the earth than is required by this principle.

In accordance with Revelle's suggestion, we conclude that the abundances of K, U, and Th in meteorites are too high for the earth. It is not necessary that these abundances shall be too high by exactly the same factor, but there is no evident criterion for distinguishing between them, and hence the same factor will be applied. In order that the rate of heat generation shall equal the rate of loss, we must decrease the abundances of these elements by the ratio $(7.00 \times 4.1 \times 10^{27}) / (9 \times 10^{27})$, or 3.19. Applying this ratio to all the radioactive elements gives 276, 0.0332, and 0.105 p.p.m. for K, U, and Th, respectively. In these calculations any contribution of heat from the earth's core is neglected, since it is difficult to understand how these very electropositive elements could be present in any important amounts in a metallic iron core.⁶ However, these elements should follow the silicates in any separation of the iron and silicate fractions, and the larger amount of iron in solar material as compared with the earth's mantle would produce a lower concentration of these elements in objects containing these larger amounts of elemental or oxidized iron. This could increase the factor to 4 instead of 3.19 for such objects. We shall use the more conservative value of 3.19, but remember that the values for heat production so calculated may be too large. Patterson concludes on the basis of his data that the factor should be 4, as compared to 3.19, and has noted this discrepancy between the rate of heat generation in meteorites and the rate of heat loss by the earth. The use of his data and factor would not change the results of this paper significantly.

The abundance curve of the elements of odd mass number in the region between

the maxima at Mg^{25} or Al^{27} and at Fe^{57} appears to be irregular and neither smooth nor similar to the curve for the even mass elements in the same region, if the usual abundance of potassium, i.e., based on 0.088 per cent by weight, is used. However, if the potassium abundance is lowered by a factor of 3.19, an irregular curve is still secured, but it is strikingly similar in its irregularity to the curve for the even mass elements. Such similarity of these curves may be expected according to the suggestions of Suess.¹⁸ Other elements, particularly Rb, Cs, Ba, Sr(?), and the rare earths, might behave similarly to potassium and hence be too abundant in the meteorites. The abundance curve in the neighborhood of these elements is not known sufficiently well to permit a reasonable decision as to whether lower abundances are indicated, but certainly there is no evident difficulty in selecting such lower abundances. Astronomical data seem to favor a higher abundance of potassium, but the variation in abundances for the elements in general in different astronomical sources or in the same source as studied by different investigators suggests that the revision suggested here is not outside probable errors of these measurements.¹⁹

The amount of potassium, uranium, and thorium assumed must not be less than that contained in the crust of the earth. Potassium constitutes about 2.6 per cent of the surface rocks of the earth, and, assuming 15–20 km. for the mean thickness of the earth's crust, we find that 50 per cent of the potassium is in the earth's crust if its mean concentration in the mantle and crust is 276 p.p.m. Similar values are secured for uranium and thorium. Since these elements are more concentrated in granites, and since granites are presumably more characteristic of the surface rocks than of the deeper rocks of the crust, no serious contradiction exists between our assumed abundances and what we know of the earth's composition.

It is assumed that the concentrations of these elements in the chondritic meteorites are higher than the cosmic abundance, and this increased concentration must be explained by some reasonable process. These elements are concentrated at the earth's surface by partial melting processes which are taking place at the present time. Potassium, uranium, and thorium are markedly concentrated in granites as compared to basalts and in both of these as compared to ultrabasic rocks. If these have been concentrated in the chondritic meteorites by processes similar to those occurring on earth, we must assume that melting processes such as those which have produced granites and basalts have been effective in the formation of some of the constituents of chondrites. Such constituents may well be the achondritic meteorites. These are of two principal kinds: those of approximately the composition of the silicates of chondrites, the chondritic (Urey and Craig) or the low-calcium (Prior) achondrites, and the basaltic (Urey and Craig) or the high-calcium (Prior) achondrites. The former might be material from which some liquid has been separated (Johnstown is very low in sodium and potassium^{14, 15}), or they might be melted chondrites, and hence potassium would not be low; this is true in some cases. Their uranium content is generally low, as would be expected; this has been shown by Davis³ and Tilton⁷ in the case of Norton County, Cumberland, and Shaw. However, the second group, which might be the liquid fraction of the melting process, does not contain high concentrations of sodium and potassium.¹⁴ The uranium contents of this group have not been investigated. We do not know of any achondritic material which would be exactly the kind of

material required to increase the concentration of potassium, uranium, and thorium in the chondritic meteorites. Further investigations are highly desired. Nevertheless, we shall assume that such material existed and was incorporated in chondritic material. The over-all process of concentration was very inefficient compared with terrestrial processes, for an increase by a factor of only 3.19 is indicated for these elements in the meteorites, instead of about 100, as in the case of the earth's crust.

The Melting of Asteroidal-Type Bodies.—Kuiper²⁰ has suggested that the asteroids and the moon have been melted by radioactive heating due to K, U, and Th. He assumes that these bodies melted internally, until only a thin outer layer of solid material remained, and then solidified by convection and cooled off by conduction, and that this left an outer layer with increased concentrations of these elements. The writer does not believe that this is a reasonable description of such a melting process. Chemical fractionation between phases, separation of the phases, and convection would occur during melting as well as during solidification. Kuiper assumes a completely quiet melting with a surface remaining intact. If the surface layer had the same composition as the melted liquid, it would surely sink into the liquid below. Moreover, we cannot assume that the liquid is more dense than the solid surface in some cases and not in others. If the liquid rises only to some distance below the solid surface in the Hyginus Cleft and the Alpine Valley of the moon, as he assumes, this must mean that the liquid is more dense than the solid, as in the case of liquid and solid water. On the other hand, he supposes that liquid flows from the moon's interior completely to the top of the Wargentín crater, which is a collision crater completely filled with what appears to have been liquid lava; this implies a less dense liquid than the solid surface of the moon, as is true of terrestrial lavas relative to the solid crust of the earth. Gilbert²¹ considered these same surface lunar features and concluded that great splashes of melted silicates produced by the collisions that formed the circular maria partially filled the Hyginus Cleft, completely filled the Wargentín crater, and produced other well-known flooded regions of the moon. It seems very doubtful that a moon with a completely molten interior is necessary or at all possible as an explanation of any of the moon's features. It is necessary to reconsider the process of melting of the moon and asteroidal bodies by radioactive heating.

We assume that planetesimals accumulated from primordial dust by some process at present unknown.²² These objects were at some temperature at least low enough so that some water condensed, since it is retained both in the earth and in the meteorites. The iron was presumably in a completely oxidized condition, since elementary iron is unstable at low temperatures in a cosmic mixture of hydrogen and water. They may have contained some ammonia and compounds of carbon. Since they accumulated at some time as grains of low thermal conductivity, radioactive heat would slowly raise their temperatures.

In general, melted terrestrial silicates are less dense than the solid silicates with which they are in chemical equilibrium. Wahl,²³ however, has argued that this condition may not be true. Bowen and Schairer²⁴ have studied the MgO-FeO-SiO₂ system, and their results show that a liquid may have a higher density than the solid with which it is in equilibrium, provided that the FeO content is high. Such high concentrations of FeO do not occur generally in the earth, so far as we know,

but they might well occur generally in the moon, which, because of its low density, probably consists of cosmic "nonvolatile" matter in which the iron is completely or nearly completely oxidized to FeO and FeS. The abundance value for sulfur as secured from the meteorites is probably too low because of the escape of hydrogen sulfide during their formation. Suess¹⁸ estimates its atomic abundance as 2,510, using silicon equal to 10,000. Iron combines with sulfur rather than with oxygen, and thus sulfur removes iron from the silicate fraction, since the iron sulfide and silicate are only slightly soluble in each other. By using Urey and Craig's¹⁶ low-iron-group abundances, which they show give material of about lunar composition as judged from densities, and using Suess's value for the sulfur abundance, percentages of minerals of the cosmic silicate fraction with the iron completely oxidized to FeS and FeO have been calculated and are given in Table 3. This neglects all minor constituents. The weight fraction of FeO in the silicate is 25 per cent. The calculations could be modified in the direction of lower percentages of iron oxide and of the olivines by assuming higher sulfur and lower iron abundances. (The writer believes that a somewhat lower abundance of iron is probable.) It seems certain that liquid high in the feldspar constituents, with some water content and thus of low density, would be produced first in a melting process. Such a liquid would rise in a gravitational field if sufficient time were available for the separation of the phases. This liquid would carry the radioactive elements K, U,

TABLE 3

	Per Cent		Per Cent
$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	9.7	$\text{FeO} \cdot \text{SiO}_2$	6.7
$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	2.7	$\text{MgO} \cdot \text{SiO}_2$	10.3
$\text{CaO} \cdot \text{SiO}_2$	3.9	$2\text{FeO} \cdot \text{SiO}_2$	29.3
		$2\text{MgO} \cdot \text{SiO}_2$	37.4

and Th and other elements not important to the present discussion from the interior toward the surface, just as has occurred in the general surface regions of the earth. This happens because the potassium goes with the feldspar fraction, and uranium and thorium are insoluble in the solid silicates. The densities would vary with the ferrous iron content, but the solubilities for these elements would not be changed markedly by the substitution of ferrous iron for magnesium ion in the melted silicates. The removal of these elements from the interior by the partial melting process would hardly be complete. Thus heating in the interior would be reduced but not completely eliminated. After this process had occurred, it might well be that any liquid produced would be as dense as, or more dense than, the solids because of the concentration of the iron in the liquid, and little or no separation of liquid and solid would occur. If the amounts of the radioactive elements characteristic of chondritic meteorites had been originally present, enough of them would probably have remained in the interior to produce complete melting, and, if this had been the case, the deep interior of the moon would be melted now. If the first liquid to melt was more dense than the solid, it should have transported the radioactive elements toward the interior. Also, if this had been the case, the surface regions of a completely molten moon would have solidified first and the radioactive elements would have concentrated in the residue and would again have been concentrated in the interior. These conditions would have resulted in a molten interior of the moon throughout all geologic time and are inconsistent with the

nonisostatic shape of the moon. For the purposes of the following discussion, we assume that the first liquid to melt will be less dense than the solid phases in contact with it.

The character of the heating process within cosmic objects of varying sizes depends on many factors. If an object were small, it would not heat up at all; if somewhat larger, it would dry out by the diffusion of water vapor to the surface; if still larger, liquid water with some substances dissolved in it might flow slowly to regions near its surface and evaporate; if larger yet, or in longer times, the lower melting silicates containing some water would flow toward the surface, break through, and spread on the surface and solidify. These latter melts would carry the radioactive elements toward the surface, and thus the rate of heating in the interior would decrease, and it would increase at regions to which the melt moved. The basalts of the earth are produced by some such process, and lava flows are never above $1,200^{\circ}$ C. in temperature. However, if the objects contained little water, the temperatures might become higher, and, if water was present, they could be considerably lower than $1,200^{\circ}$ C. The processes just outlined for the largest objects might apply to the asteroids and the moon. It is not at all certain that the object would ever melt completely. Even the surface regions would probably never be melted except locally and temporarily, and subsurface temperatures would remain somewhere near the melting point of hydrous silicates.

Using the abundances of K, U, and Th given above, we can calculate the amounts of heat which would be generated by radioactive substances. Since the date for the formation of the solar system seems to be some 4.5×10^9 years ago,^{25, 26} and some time is needed for radioactive heating, we shall calculate these heat energies for the last 4.5×10^9 and 5.5×10^9 years and for the interval between 5.5 and 4.5 billion years ago. The results are given in Table 4. The heat of fusion of silicates

TABLE 4

HEAT ENERGY IN JOULES PER GRAM GENERATED IN INDICATED TIMES (K = 276 p.p.m., U = 0.0332 p.p.m., Th = 0.105 p.p.m.)			
Nuclide	4.5×10^9 Years to Present	5.5×10^9 Years to Present	5.5×10^9 Years to 4.5×10^9 Years
K ⁴⁰	600	1,080	480
Th ²³²	440	550	110
U ²³⁵	340	910	570
U ²³⁸	630	840	210
Total	2,010	3,380	1,370

of cosmic composition is about 400 joules per gram, and the heat capacity is about 1 joule per gram at low temperatures. The heat of fusion of water is 333 joules and of vaporization 2,260 joules per gram; hence any water in these objects would require considerable heat for its melting and evaporation. Some 2,000 joules of heat are required to raise the temperature of silicates from ordinary temperatures to their melting points and to melt them even if no free water is present. The 1,370 joules of total heat per gram given in the last column of Table 4 is not sufficient, and yet some 10^9 years are required for its production. It is difficult to meet the requirements of no net heating or cooling of the earth at the present time and at the same time melt the moon or asteroids by radioactive heat.

The Chondritic Meteorites.—Wasserburg and Hayden²⁶ have determined the ages of the chondritic meteorites by the K⁴⁰-A⁴⁰ method and find 4.7×10^9 and 4.8×10^9 years; and Patterson *et al.*,²⁵ from the ratio of Pb²⁰⁶ to Pb²⁰⁷ in the chondrites, assuming that the lead of Canyon Diablo and Henbury iron meteorites gives the

primitive isotopic ratio, find 4.5×10^9 years. Since the half-lives of U^{235} and U^{238} are more reliably known than the half-life and branching ratio of K^{40} , Patterson's date is probably the more reliable. The K^{40} - A^{40} dates are particularly informative. They mean that A^{40} has not been lost from the materials of these meteorites for this length of time, and this means that all melting processes which produced the minerals of these objects occurred more than 4.5×10^9 years ago. The chondrules of these objects are best explained as having been produced as molten droplets which have only partly crystallized even at the present time. The process which broke up the crystals and produced the melted chondrules was one of considerable violence and would result in the loss of A^{40} from these objects. It seems most likely that this process also occurred before or at 4.5 – 4.8×10^9 years ago. The fragments could not have accumulated much later by falling on an asteroidal-type body, because small objects some millimeters and smaller, such as the chondrules, would have been moved toward the sun, due to the Poynting-Robertson effect, and would no longer remain in the neighborhood of the asteroids after the sun became a bright star.²⁷ The chondritic meteorites contain bits of plesite, kamacite, and taenite, the iron-nickel alloys of the Widmanstätten figures of the iron meteorites.²⁸ Hence this differentiation had taken place before these dates. This process of producing the chondrites required as a minimum (1) the reduction of oxidized iron to metal, the melting of the iron, its accumulation into massive masses, and its slow cooling to form the iron-nickel alloys; (2) the melting of silicates and their crystallization to produce the minerals of the chondrites and achondrites; (3) the violent brecciation of these materials; and (4) the accumulation of these materials into the chondrites. The processes were partially repeated, since pieces of chondrites and achondrites of particular distinctive types are often imbedded in stone meteorites of other types.²⁹ No ages of these polymict meteorites have been measured. The main process of meteorite formation was evidently completed 4.5×10^9 or more years ago. It is difficult to account by radioactive heating for the melting which produced the materials of the meteorites and at the same time to account for the heat balance of the earth at the present time. A somewhat larger amount of radioactive elements or an age for asteroidal-type objects even greater than 5.5×10^9 years would be required. One wonders where these objects were and what evolutionary processes of the solar system were occurring during the long time between the accumulation of such objects and the period of violent collisions which formed the chondrites some 4.5×10^9 years ago.

Yet we have assumed that the radioactive elements have been concentrated in the meteorites by a factor of 3.19 by a melting process. We shall try to outline a possible radioactive heating process by which this could have occurred in spite of the obvious difficulties noted above. As the temperature of an asteroidal body slowly increased, consolidation of its material would occur and partial melting of its lower melting constituents would take place. The radioactive elements K, U, and Th would dissolve in the first liquid, and this liquid would flow toward the surface. This would decrease the heating on the interior and increase that toward the surface. The exact events would defy any confident quantitative description; they depend on the strength of the gravitational field, the water content (which affects the viscosity and melting points), and the thermal conductivity of the object. This melting process is apparently occurring on the earth at the present time, and even in this case no quantitative description has been possible. However, the

differentiation of the surface materials required in order to produce increased concentrations of the radioactive elements in the meteorites does not appear to be impossible. Some iron may even have melted in regions where the radioactive elements were concentrated. If the massive metallic iron-nickel was produced in this way, then reducing agents such as carbon compounds must have been present to reduce the oxidized iron present in the primitive materials. Such reduction processes would consume heat, as would the vaporization of volatiles generally. Also, the different chemical composition of the high and low iron groups¹⁶ and a mechanism for the intense brecciation of the chondrites must be explained. It seems most likely that this chemical fractionation is related to the general fractionation between the silicate and metallic iron fractions required to explain the varying densities of the planets.³⁰

The carbonaceous chondrites contain appreciable quantities of water and other volatiles, and chemical analyses which will be published shortly by H. Wiik show that these objects belong in the Urey and Craig high iron group.¹⁶ X-ray diffraction studies made by Miss Ann Pletinger and the writer show that these objects are probably ordinary chondrites which have been subjected to water solutions. The Orgueil and Ivuna meteorites, for example, show the X-ray diffraction patterns of magnetite with only very faint indications of any other pattern, and magnetite is the stable oxide produced by the action of water on metallic iron. Other carbonaceous chondrites indicate that hydrated silicates are present in addition. Though we may be able to account for the increased concentrations of the radioactive elements, and possibly for the fusion of iron and silicates by radioactive heating due to K, U, and Th over a long period of time, many difficult points remain, and other possibilities should be considered.

However, one point must be made definite. The discussion of this paper is consistent only if the chondritic meteorites originated from the surface regions of an asteroidal body. This requires revision of previously expressed views of many people, including those of the writer.

The Melting of the Moon.—The moon has differences in moments of inertia calculated from its dynamical motions which indicate a projection toward and away from the earth about 1 km. in height, as compared to the polar radius, whereas the equilibrium height should be only about one-seventeenth of this.³¹ The writer has maintained that this indicates great strength in the moon, that it is not now molten on the interior, and that, if it had ever been molten, even moderate amounts of radioactive heating would have maintained its temperature near the melting points of the silicates. This calculation has been repeated using more recent data, and the previous conclusion seems to be justified. The writer suggested that the irregular shape might be due to the fall of the large planetesimals on the surface of the moon. Regardless of the time and mode of formation of this projection, it must be true that the moon has had a very rigid structure since it was formed. By contrast, Kuiper²⁰ concludes that this projection is not due to a frozen tidal wave but that it was formed by the addition of mass to localized areas by the objects which formed the maria and that these events occurred at or near the time when the moon was totally or largely in a melted state. Kuiper's assumptions appear to be inconsistent. Surely the moon would take an equilibrium shape when completely melted, regardless of whether objects fell on it or not. This nonequilibrium shape of the moon is an important datum in considering its thermal history.

The writer has regarded the moon as a primitive object like the planetesimals, which he found necessary for the understanding of the chemical problems relating to the origin of the solar system. The primary argument for this view depends on the moon's density. As is well known, this density is 3.34, or about 3.31 corrected for pressure. The mean temperature of the moon can hardly be 300° K. If it is 1,200° C., the density of its material would be about 3.45 at room temperature and zero pressure, and this is about the density expected for cosmic nonvolatile material if all the iron has been oxidized to FeO and FeS.¹⁶ The figures can be manipulated to some extent by assuming the presence of some water in the moon's substance, which would lower the density, and of some metallic iron, which would raise its density. This composition of the moon requires that it have been separated from gases of cosmic composition at a low temperature, for otherwise the iron would be substantially completely reduced to the metallic state.³²

But some radioactive heating of the moon must have occurred. This has been considered previously by the writer.³³ The abundance of potassium in the meteorites was taken as 0.2 per cent, whereas it is now considered to be 0.088 per cent. The abundance of uranium was taken as 1.3×10^{-8} gm/gm, while now it appears to be about eight times as great; and the age was taken as 3×10^9 years, while now it is taken as 4.5×10^9 years. Needless to say, the previous calculations need revision. A simple substitution of the new values for the elements K, U, and Th in chondritic meteorites leads to a highly melted moon and earth, as explained before. However, the lower abundances assumed in this paper lead to an acceptable conclusion. A heating process such as that described for an asteroidal body can be applied qualitatively without change to the moon. Due to greater size and gravitational field, the process would be quantitatively different. The increased field would favor the separation of liquid and solid silicates, but viscosities might be increased as well by higher pressures. The transfer of radioactive elements to the surface or toward the surface would enable the radioactive heat to be lost more readily than was previously calculated by the writer. It is possible that great rigidity would be preserved in the moon since the time of formation of the lunar projection toward and away from the earth. A little consideration of the data of Table 4 shows that it is only necessary that about one-half of the original concentration of K, U, and Th should have been transported to the outer parts of the moon, from which the heat is readily lost by conduction, in order that the temperature of the moon should stay below the melting point of its silicates, if the moon accumulated some 5.5×10^9 years ago. The figures can be manipulated in various ways, again, because of uncertainties regarding initial temperatures, thermal conductivity and the consequent loss of heat, amount of heat generated as determined by amounts of radioactive materials and age, etc.; but one sees that the nonequilibrium shape may well have been formed some 4.5×10^9 years ago and still remain today on the moon.

But, if heating processes other than radioactive heating by U, Th, and K (see below) produced the melting in the meteorites, then the moon and asteroids may have formed some 4.5×10^9 instead of 5.5×10^9 years ago. In this case a slightly smaller concentration of these elements in the moon than is assumed in this paper would mean that no large transfer of these elements to the surface is required to avoid melting of the moon, provided that the moon accumulated at low temperatures.

Heat Balance of the Earth and Mars.—The earth is a derived object and not a primitive one. This is shown by the essential absence of the high-atomic-weight inert gases. These gases must have escaped from the earth's protoplanet before the earth had accumulated and while its mass was distributed over a large volume. The present material of the earth must have been in solid or liquid form, for otherwise the inert gases could not have been separated from the volatilized "nonvolatile" fraction, and it must have been at low temperatures and hence solid, for otherwise the more volatile constituents of the "nonvolatile" fraction would have escaped,³³ which is not the case. The writer has described this stage as a miniature globular-cluster type of object. When the inert gases and most of the hydrogen, water, methane, and ammonia were gone, only then could the earth have accumulated. It is a derived object, and younger than the moon. (The writer would not try to state how much younger.) The total heat generated in the last 4.5 billion years was thus 2,000 joules per gram, and at the present rate of loss of heat the earth would have lost 1,000 joules of heat per gram. It seems not unreasonable that the rate of loss of heat may have been greater in the past. Hence the earth can quite easily have remained at temperatures comparable to those of the present time even if the energy of the formation of the core is included. In fact, it is difficult to account for the high values of the internal temperatures generally recognized as existing within the earth,³⁴ unless the energy of the formation of the core is included if it accumulated at low temperature, as the writer has argued on evidence that has not been criticized.³⁵ The energy of core formation has been estimated as 1.67×10^{38} ergs,³⁶ with an error which is difficult to estimate. The radioactive heating during 4.5×10^9 years is calculated to be 2×10^{10} ergs per gram of the mantle, or a total of 8.2×10^{37} ergs. At the present rate of heat loss of 9×10^{27} ergs per year a total loss of 4.05×10^{37} has occurred. This gives a total of 20.85×10^{37} ergs, or 3,500 joules per gram of the earth. If the loss of heat was larger in the past than it is now, which seems probable, no insuperable difficulties in regard to the heat balance of the earth exist. In fact, according to Revelle, the earth has always been able to dissipate its heat approximately as rapidly as it is generated. Proponents of an initially molten earth will secure this additional heat from the "original" heat rather than from the energy of formation of the core.

The Clairaut constant for Mars is 1.22, using Trumpler's value for its radius, or 1.19 using Kuiper's value.³⁷ These values are so close to the value for a planet of uniform density, namely, 1.25, that they indicate that even the difference between them is due to increased densities in the interior produced by compression only. The density of Mars is 4.18, which gives 3.96 estimated for zero pressure. This indicates that the planet contains about 30 per cent by weight of metallic iron. These conclusions can be changed by a redetermination of the radius of Mars, but for the present the conclusion in regard to Mars is that, though it contains approximately 30 per cent of metallic iron, it has no core or only a small one. This conclusion is inconsistent with the high rate of generation of heat calculated in Table 2, for the planet would have melted and formed a core regardless of its temperature of formation.

However, the 2,000 joules per gram of cosmic matter generated in 4.5×10^9 years (Table 4) is a manageable figure, at least. Some loss of heat has occurred. Though there seem to be no mountains on Mars, lava flows may have occurred.

Solid iron would hardly sink through solid silicates, and at ordinary pressures silicates melt below the melting point of iron-nickel of meteoritic composition and, in fact, if some water is present, some 500° below the melting point of iron. Hence the partial transfer of radioactive elements from the interior of Mars to its surface may have occurred. McLaughlin³⁸ has suggested that volcanoes do occur on Mars. With a moderate temperature of formation some 4.5×10^9 years ago, the low concentrations of the radioactive elements assumed here, and their possible transfer to the surface to a reasonable degree, the low temperature of the planet as indicated by its lack of a core can be understood.

Effect of Other Permissible Abundances of K, U, and Th.—Up to this point it has been assumed that the particular choice of abundances for K, U, and Th, namely, 276, 0.0332, and 0.105 p.p.m., respectively, is rigorously correct. This, of course, is only a working hypothesis. The total heat generated may be larger if the earth is heating up or lower if the earth is cooling down. Because of the marked chemical similarity of UO_2 and ThO_2 , these two elements should accompany each other and should be concentrated in the chondrites to the same degree. On the other hand, potassium may not be equally concentrated in the chondrites as compared to uranium and thorium. Thus it is possible that the cosmic abundance of potassium is higher or lower and that of the uranium and thorium lower or higher, respectively, than has been assumed. If the potassium abundance is higher than has been assumed, somewhat more heat would be generated during geologic time and somewhat more heating would be available in earlier times, and if it is lower somewhat less heating would be available. Such amounts of heat may be consistent with the present high rigidity of the moon and the absence of a core in Mars. As stated previously, it seems more likely to the writer that the total amounts of these elements are, in fact, lower than has been assumed in this paper. In this paper an attempt is made to show that these data on the moon and Mars and the radioactive heat required by the assumption of equality of the rate of loss and generation of heat in the earth can be consistent with each other.

As was pointed out previously, an alternative assumption would be that the earth, the moon, and Mars had lost part of their radioactive elements during their formation, while the meteorites retained them in more nearly their proper cosmic abundances. Recently Dr. H. E. Suess outlined a possible course of events to the writer which might have accomplished this and which is presented here with his permission.

After the elements were synthesized at high temperatures, the mass cooled down and condensation of the elements occurred, with considerable segregation of the elements in different solid particles such as metallic iron, the silicates, and oxides. These crystals had different densities and, during the formation of the planets, became sorted mechanically, with variable amounts of the different chemical substances being retained by the different planets, thus producing the different densities of the planets. In this process the radioactive elements were lost preferentially relative to the silicate fraction, while the silicate fraction itself was being lost relative to the metallic fraction. Von Weizsäcker concludes that an extended system such as a protoplanet having high angular momentum would separate into a central body, the planet, and a fraction which is lost to space and which carries the excess angular momentum. However, the details of the process are too complex

for exact mathematical and physical description. Such a process might explain Mars and the earth, but some special assumptions must be made for the moon, which did not lose much of its silicate fraction as compared to its metallic fraction, that is, if it has any iron fraction at all.

The suggestion does not seem to be an impossible one at all in view of the uncertainty of the process of planet formation. However, it is difficult to say what the physical differences between the fraction which carried the radioactive elements and the other fractions were, since these elements are so definitely oxyphile in character and are, in fact, among the most electropositive elements. These elements should have condensed as part of some silicate fraction, and this fraction could hardly have had a density very different from that of any other silicate fraction. What is required is a separation of the one fraction from the other, since these elements—potassium, uranium and thorium—will not be present in the metallic phase. Perhaps some difference in particle size may have made a separation possible.

It is still necessary to secure an accumulation of the bodies which produced the meteorites and to account for the melting processes which produced the silicate minerals and the massive iron of the meteorites. Also, we must account for the massive objects of high tensile strength which plowed out the grooves in the center of the moon's disk.³⁹

If larger amounts of the radioactive elements were present in the primordial materials, greater heating effects could be produced. Yet the data of Table 2 show that some 5×10^8 years, i.e., from 5×10^9 to 4.5×10^9 years ago, would be required to produce some 1,860 joules of heat per gram, which is somewhat less than the amount required to raise meteoritic material from low temperatures to the melting point and melt it, but sufficient to *partially* melt such material in completely insulated bodies. This is a long period of time, and one wonders at the required series of events, i.e., an accumulation of bodies large enough to be thermally insulated, a quiet period of 5×10^8 years for radioactive heating, a violent brecciation process to produce chondrites, and then no processes sufficiently violent to remove A⁴⁰ for the next 4.5×10^9 years!

A Reconsideration of Radioactive and Other Sources of Heat.—The arguments of this paper have been presented as favorably to the radioactive heating postulate as possible, but it is very difficult to believe that heating by K, U, and Th is a feasible explanation for the high-temperature stage required to produce the meteorites and to produce the fractionation of the silicate and metallic phases in the planets generally.³⁰ Urey⁴⁰ has considered three sources for these high temperatures, the required chemical separations, and the collisional processes for the formation of the meteorites: (1) Evaporation of silicates by a high-temperature sun early in its history was suggested. There appears to be no evidence for such behavior of a new star, but we do not know everything about the process of forming stars. (2) An attempt was made to modify the Eucken-Kuiper condensation process in protoplanets in such a way as to avoid fractional loss of the more volatile elements. It is difficult to secure high temperatures by the adiabatic compression of gases and at the same time to lose those gases, but the process has not been described quantitatively because of its great complexity. (3) It was postulated that the planetesimals of the asteroidal type antedated the formation of the sun and that

the solar nebula was formed during a collision of the new sun with a gas, dust, and planetesimal cloud, with the heating and collisional processes occurring during this collision. It seems possible that any of these heating processes may have produced an increase in the K, U, and Th concentrations on the surfaces of the asteroids by a factor of 3.19 or more, as required by the present calculations, though it is easier to describe plausible models if radioactive heating is assumed.

The age of the solar system now appears to be so great that we may question whether the accretion of substantial objects did not occur so soon after the synthesis of the elements that some of the radioelements with half-lives of some million years may not have completely decayed when this occurred. Blaauw⁴¹ has shown that the stars in the Perseus cluster must have originated 1.5×10^6 years ago and hence that some very rapid mechanism for the formation of stars exists. Without a model for the formation of these planetesimals, it seems impossible to conclude that they could not also have formed in such a period of time. There are eight known radioactive nuclides that may be important as sources of heat within 10^6 – 10^7 years after the synthesis of the elements. These are listed in Table 5, together

TABLE 5
HEAT ENERGIES OF SOME RADIOACTIVE NUCLIDES

Nuclide	Heat Energy (Mev)	Half-Life (Years)	Abundance of Neighboring Nuclide (P.p.m.)	Energy (Ergs/Gm of Nuclide)	Energy (Joules/Gm of Meteorite)
Al ²⁶	β^+ 3.3	10^6	$1/2$ Mg ²⁶ 7500	1.2×10^{17}	9×10^7
Cl ³⁶	β^- 0.285	4.4×10^5	Cl ³⁷ 120	6.7×10^{15}	8×10^4
Zr ⁴³	β^- 0.021	5×10^{-6}	$1/2$ Nb ⁹³ 0.2	2.2×10^{14}	4
Pd ¹⁰⁷	β^- 0.035	7×10^6	$1/2$ Ag ¹⁰⁷ 0.67	1.1×10^{14}	7
I ¹²⁹	β^- 0.052	1.7×10^7	I ^{127*} 1.25	6.7×10^{14}	84
	γ 0.038				
	0.090				
Cs ¹³⁵	β^- 0.070	2.9×10^6	Ba ¹³⁵ 0.19	5.0×10^{14}	10
U ²³⁶	4.58	2.39×10^7	U ²³⁸ † 0.0666	1.87×10^{16}	125
Np ²³⁷	44.01	2.2×10^6	$(2/3)$ U ²³⁸ † 0.0222	1.77×10^{17}	394

* The abundance of I¹²⁷ is probably too high by a factor of 5.

† One-third of the abundance of U²³⁸ 4.5×10^6 years ago is used as an estimate of the primordial abundance of the odd mass-odd atomic number element Np²³⁷, and that of U²³⁶ as equal to that of U²³⁸ at the same time.

with their heat energies of disintegration (35 per cent of the maximum beta-ray energies are used again), their half-lives, the abundance of a similar stable element which is taken as an estimate of their primordial abundance, and the energy per gram of nuclide and per gram of meteorite produced by their complete disintegration. The calculations are very approximate, but it seems doubtful whether any nuclide except Al²⁶ and Cl³⁶, or some other at present unknown nuclides, need be considered, and Cl³⁶ has such a short half-life that its effect would be negligible as compared to Al²⁶. Hence only this recently discovered nuclide Al²⁶ need be considered at all.⁴² Even after the lapse of some 15 half-lives, the amount of remaining heat from the Al²⁶ would be 3,000 joules per gram. This element also is concentrated at the earth's surface by partial fusion processes. If this heat was available, a great variety of assumptions can be made, since the amount of heat depends so markedly on the time of formation of insulated bodies.

The possibility of radioactive heating as a source of these heating processes has been considered by the writer previously, but heating by such means has seemed to him inconsistent with other facts. Uranium, thorium, and potassium either re-

quire such long periods of time to produce the early heating processes, i.e., some 10^9 years, that they seemed highly improbable, or their abundances must be so high that the irregular shape of the moon and the absence of a core in Mars could not be understood. Radioactive elements in the mass range above iron could not furnish a sufficient amount of heat to be important, as is also true of U^{238} and Np^{237} , unless other, as yet unknown radioactive nuclides exist. Cl^{36} has such a short half-life that very rapid accumulation of the planetesimals would be necessary, and this seemed improbable. However, Al^{26} perhaps gives a real possibility of explaining these heating processes. Its energy is large, and perhaps accumulation of planetesimals would be possible within some 15×10^6 years, that is, not too quickly or too slowly, and hence some proper amount of heating is possible.

The order of events becomes the synthesis of the elements during some major process such as that which formed the Perseus cluster of stars, the accumulation of the sun and planetesimals of the asteroidal and lunar type within some 10^7 years, heating due to Al^{26} , a fractionation process which partially separated the silicate and metallic fractions and separated these in varying amounts in different planets, and accumulation of the planets during some fairly long time. These processes included some intense collisional mechanism during which the brecciated structure of the meteorites was formed. All these processes may well have occurred some $4.5\text{--}5.0 \times 10^9$ years ago, during a time span of some 10^7 years.

It seems most probable that some combination of these various processes occurred during the formation of the solar system.

Conclusions.—Reasons have been given for believing that the abundances of the elements K, U, and Th in the chondritic meteorites are higher than the mean abundances of these elements in planetary bodies by about a factor of 3.19. Using decreased abundances of these elements, it is shown that the thermal properties of the earth, the permanent nonequilibrium shape of the moon, and the absence of a core in the planet Mars can be understood. The lower abundance of potassium gives a more regular curve for the abundance of elements in this region of the periodic system, though it disagrees with the astronomical data in this respect. It is difficult to secure sufficient heat for this purpose on the basis of abundances of K, U, and Th as used in this paper. It is suggested that Al^{26} may have supplied the radioactive heat for this purpose and that other heating processes previously suggested may have been important as well. As an alternative, it is also possible that depletion of these radioactive elements in the earth, the moon, and Mars during their formation may account for the lower abundances of these elements required to secure reasonable thermal histories for these planets.

The writer is indebted to Professor Roger Revelle for his statement of the conclusion that the rate of heat loss from the earth has always been approximately equal to the rate of heat generation. This idea gave the key to a solution of problems that have troubled me for several years. Thanks are also due to Dr. C. Patterson for a discussion of his analytical results on lead and uranium in meteorites before they were published, to Professor Julian Goldschmidt and Dr. Harmon Craig for their discussion of the melting processes in silicates, to Dr. Maria Goeppert Mayer for a very constructive criticism of this paper, and to Dr. H. E. Suess for his presentation of alternative possibilities noted in the text. Apologies are due

Professor F. A. Paneth and his co-workers for the writer's skepticism in regard to their determinations of the uranium and thorium contents of meteorites for these several years.

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SOLUTION OF A PROCESS OF RANDOM GENETIC DRIFT WITH A CONTINUOUS MODEL*

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The problem of random genetic drift in finite populations due to random sampling of gametes in reproduction was first treated mathematically by R. A. Fisher,¹ using a differential equation. Fisher's general method was appropriate, but owing to the omission of a term in the equation, his result for the rate of decay of variance was only half large enough. The correct solution for the state of steady decay was first supplied by S. Wright,² using the method of path coefficients and an integral equation.

Later Fisher³ corrected his results and also elaborated the terminal part of the distribution in the statistical equilibrium by his method of functional equations.

In all these works, however, it was assumed that a state of steady decay had been attained, but nothing was known about the complete solution which might show how the process finally leads to the state of steady decay. The present writer,⁴ by calculating the moments of the distribution and with the help of the Fokker-Planck equation, obtained a solution which assumed an infinite series under the continuous model, showing that the process approaches asymptotically the state of steady decay. At that time, however, only the first few coefficients in the terms of the series could be determined. Pursuing the problem further, he arrived at the complete solution, which will be reported here. After obtaining these results, the writer recently discovered the work of S. Goldberg.⁵ In his unpublished thesis Goldberg