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AGE OF THE MOON, CHEMICAL COMPOSITION, GEOLOGICAL ASPECTS, STRESS AND COOLING HISTORY

by

Harold C. Urey

NsG-541 U. California
NGL-03-002-017 U. Arizona

The topics to be discussed here are indicated by the title of this presentation. All of these with the exception of the geology of the moon will be included, lunar geology is excluded since this material will be covered by others at this meeting. It should be mentioned that much of what is to be discussed here can be found in the author's chapter of the book "Physics and Astronomy of the Moon," edited by Professor Kopal. Several items of interest, not presently in print, will be added at this presentation; it is expected that these will appear in the literature sometime in the near future.

The first subject to be considered is the age of the moon. The moon is a satellite of the earth; and in estimating its age one must be concerned, to some extent, about the process of origin. How did it get where it is and in particular what is the age of the surface? In attempting to answer these questions it would be most gratifying to have a sample of the lunar surface so that its age might be estimated by potassium argon dating. It is quite possible that argon would be absent in the equatorial regions though it is felt that it would be found in the polar regions. Hence, we should be able to determine when the major features of the lunar surface were formed. It has been my contention for some time that most of the surface features of the moon are ancient; and it is expected that when dating of the kind referred to here is done, these will prove to be from 4.5 to 4.7 billion

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years old. It has been my view that the surface features were acquired primarily during the period of origin of the moon and that this occurred at about the time when the meteorites were formed.

Incidentally, the meteorites have been found to be rather complicated objects. Their age has been estimated, from radioactive dating methods, to be about 4.5 to 4.7 billion years. It is quite likely that these objects were formed with the solar system and acquired their physical and chemical properties at that time.

In Figure I is shown a segment of the lunar surface. This particular photograph was made some five years ago. It was produced by a technique which eliminates foreshortening of the image. The method employed is to project pictures of the moon onto a white sphere and to photograph this projection from directly above the spherical surface. The region shown here is Mare Imbrium; it is that region first discussed by Gilbert in his work published in 1893.

According to the formation shown, an object, coming from the northeast, collided with the lunar surface and plowed out the feature known as Sinus Iridum. This is outlined by the smaller circle in Figure I. This object probably produced a large bulge on the moon and scattered material over the surface, producing a great fan-shaped pattern of ridges and grooves extending all the way to the center of the lunar disk. The edge of the maria was probably produced when the shock wave subsided and material settled back, breaking off, producing this structural feature. There is a good reason to believe that the material thrown out by this collision will be found in the older, pre-Imbrian craters of the moon; some craters, formed later, quite naturally will not have Imbrian material in their interiors. It is most reasonable to believe that all these features were produced by a single event,

that collision did occur and produced the total structural feature shown in the Figure.*

There are other circular craters and maria on the moon. For instance Mare Serenitatis, Mare Humorum, Mare Nectaris and Mare Crisium, all of these are likely to be the result of large objects colliding with the moon. Other maria on the moon, such as Oceanus Procellarum, Mare Nubium and Tranquillitatis look as though they might be the result of a lava flooding and solidification. There is a difference of opinion concerning lunar lava flow; some students of the moon contend that the lava came from the interior, much like it does on earth, while others subscribe to Gilbert's suggestion that the lava is a consequence of the heating due to collision.

In regard to the collision producing Sinus Iridum, one might ask the question, where did the object come from that produced this large effect? It should be noticed that it is not possible to maintain a large object, crossing the Earth-Moon orbit, for any appreciable time without a collision occuring. Such a collision must have occurred in a relatively short time, say a hundred million years or so, after it first appeared crossing the Earth's orbital path.

There are other reasons for believing that such an event occurred early in time. Mare Serenitatis is a circular mare of a gray color while Mare Tranquillitatis is a very irregular mare of a darker color bordering Serenitatis on the west. The question arising here is which occurred first, Mare Serenitatis or Mare Imbrium? Had the first formation been Mare Imbrium then it would be expected that the radiating ridges south of Mare Serenitatis would have undergone a great deal of

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* Recently Hartmann and Kuiper have published much more beautiful pictures than that produced here, but I believe that their interpretation is quite incorrect and hence this older and less elegant picture is used to illustrate these features of the moon.

destruction. Had Mare Serenitatis been formed first, then why are mountain ridges on this mare not also radiating from the collision area on Mare Imbrium? One suggestion is that this all came about because Mare Serenitatis was still fluid, or melted, at the time of the collision which produced Mare Imbrium. Fluidity in the sense of a dust gas mixture should not be excluded as possible. Then there is the question of how long did it stay melted? Some few years ago the author made some calculations on this and concluded that the time was rather short - some few thousand years or so. The two events producing these maria must have occurred near to each other in time. As a matter of fact, the large number and distribution of craters on the moon suggests that events occurred somewhat in the following order: first craters were formed, then maria, then other craters, etc. All of this occurred in a short span of time; then the bombardment stopped and nothing else on this scale has occurred since. It is the contention that the surface features of the moon were fashioned toward the terminal stage of the Earth-Moon formation and that little crater formation has occurred since then. An exception to this could be the formation of the great ray craters of the Moon; all others are probably very ancient for the most part.

One other striking feature in regard to Mare Serenitatis is the dark line in its western area, and the darker area in and around this region. This looks to be the result of a lava flow up over the whole of the area. It is quite possible that this was produced when the Imbrian collision occurred, spreading material over much of Mare Serenitatis, which in its solidification produced the line mentioned above. It may be possible to fit some similar reasoning to the hypothesis of deep dust in the lunar maria.

One should not believe that these statements prove the point. They are merely

reasonable arguments; no one really knows anything certain about these subjects at all. All that is being done here is to put forward what look to be reasonable argument's with the hope that in time the facts will become known and the hypotheses verified or refuted. If one does not like or agree with such statements then he should not be too concerned since there is no way of absolutely ascertaining many of these things at present.

For reasons of this kind I believe the moon acquired its surface features in a relatively short period of time, and did so a very long time ago. Particularly, it did so during the origin of the solar system.

Toward the end of this discussion some ideas regarding the origin of the moon will be mentioned; that the rather short time scale for the surface features of the moon may have resulted during its capture, while the earth still had some smaller objects moving about it, objects which were the residue of its own accumulation. In a relatively short span of time the satellite swept up this terrestrial trash; aside from some few meteorite impacts since that time, and possibly some small amounts of volcanic activity in its early history, the moon's features were thus formed.

Chemical Composition of the Moon

Next we should look at the chemical composition of the moon. What is meant by this is the chemical composition of the object as a whole. Unfortunately we can only estimate the composition, and this from an interpretation of its low mean density.

The density of the moon is well established from a reasonable knowledge of its mass and size; the value of density is currently taken as 3.34 grams/cm^3. This applies to the moon at a considerable internal pressure and at elevated internal temperatures; temperatures larger than surface levels. The pressure, internal to

the moon, can be rather adequately estimated from the well known hydrostatic expression

$$p = \frac{2}{3} \pi G \rho^2 (a^2 - r^2)$$

where G is the gravitational constant, ρ is the density (assumed uniform for the moon) and a is the major radius of the body. This expression should give the internal pressure quite accurately; there will be some small errors but these are not important in our present discussion.

The temperature of the moon, and particularly its internal temperature, is considerably more difficult to determine though several estimates have been made. Some years ago I estimated the temperature of the moon from a study of its thermal history. And with a knowledge of the coefficients of compressibility and thermal expansion for materials which might make up the moon, calculations of the lunar density were also made. Assuming the compressibility of the moon to be about the same as that of olivine or pyroxene, the estimate of density as a round value is 3.40 grams/cm^3. This value is the average of estimates at low pressures and terrestrial surface temperature from approximate values for the temperature distribution and calculated pressures; the range of calculated values varied from 3.38 to 3.41 grams/cm^3. It is possible to estimate the composition of the moon by comparing the values here with those of materials which are close to the make-up of the meteorites. This choice of comparison is made on the basis that the meteorites will provide material samples which more nearly approximate primordial material than will the earth.

Now, starting with the chondritic meteorites, of which there are two distinct groups - one having a density of 3.57 grams/cm^3 (calculated from the observed composition) the other having a density of 3.76 grams/cm^3 - it is apparent that the moon is less dense than these objects. Incidentally, the calculated densities for

these meteorites is slightly larger than the observed values; probably this can be attributed to the fact that the observed values are an average taken by many persons over a rather long period of time. Too, it is reasonable to expect that the meteorites are porous which would suggest a lower density. Now suppose that in the low-iron chondrites the albite is converted to jadeite and the SiO_2 is taken up as magnesium metasilicates ($MgSiO_3$); the density is then calculated to be 3.65 grams/cm^3 instead of the 3.57 grams/cm^3 as calculated from the observed composition.

With these various calculated values we next ask how much iron must be removed from the meteorites to make their residue equal the calculated density for the moon. This has been done, and it is found that if the iron in the residue appears as FeS and Fe then the required content is 10.78 per cent. If the iron is to be present as FeO then the per cent present in the chondrite residue should be 11.52. These calculations are based on the assumption that the basic physical characteristics are the same as those of olivine, and that the mean temperature of the moon is 1100°C. If the constants for the calculations are altered, say choose the physical characteristics of enstatite, then the iron content of the residue is altered and the average density of the moon is slightly changed. It is these variations of probable material makeup which gives the range of values for density as stated previously.*

It is interesting to note that the abundance of iron in the moon is probably below the level of that found in the chondritic meteorites. To some extent this lends support to the idea that the moon is a primitive body having the same proportion of iron as the sun. Some investigators have calculated the solar abundance, and that for the origin of the elements, to be considerably below the value obtained

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* See H. C. Urey, J. Geophys. Res. 64, 1721 (1959).

from a study of the chondrites. Suess and Urey have made calculations of this value and obtained 6×10^5, relative to silicon taken at 10^6. The Aller value for solar abundance of iron is 1.4×10^6. It is apparent that there is a discrepancy here by a factor of about 3 or 4. In this respect it may be concluded that the earth has a material makeup much like that of the chondrites, but the sun and moon contain much less iron. Of course in the final analysis this question, too, will be answered when a sample of the lunar surface becomes available for study. Such a sample alone will be of great importance since its analysis has a direct bearing on the problem of the origin of the solar system and the synthesis of elements present there.

All in all we might conclude that the moon has a bulk composition more nearly like that of the sun. It appears to be of a material like that of the sun with the gaseous components eliminated, and containing some small fraction of high density material accumulated in the processes which produced the high density earth.

Of course it is likely that the discrepancy in density between the moon and the meteorites can be accounted for by assuming other models. One such case is to assume that the lunar rocks have sufficient water content to reduce the meteorite density to that of the moon. One would only have to assume about a two per cent water content to provide the necessary reduction. Of course such a content of water would cause a lowering of the silicates melting point which would in turn suggest a greater volcanic activity and more evidence of lava flow than is presently observed. This does not suggest that the lunar surface material does not contain water; it does provide a reasonable doubt that the moon as a whole would have this large a percentage.

Another substance which could be present, in large enough quantities to properly reduce the chondritic density to that of the moon, is graphite. Graphite is present in the meteorites, though there would have to be about ten per cent (by weight) of graphite to provide a proper density. Graphite might react with iron oxides to give CO and CO_2 and if these escaped the density of the moon would increase. Of course this too remains as a possibility since the internal temperature of the moon is largely unknown and the chemical reactions may have been sufficiently retarded to allow high percentages of carbon to remain intact.

The curious bulk composition of the moon has led to speculations regarding its origin, beginning in the last century with Sir George Darwin who proposed that the moon escaped from the earth. His reason for doing so was to account for the low density of the moon; his suggestion was that the moon was formed by the throwing off of the lower density earth surface material due to tidal action. A repetition of his calculations by Jeffries, and by Moulton, during the present century have led to a different conclusion. Also, according to Lyttleton, in his book, "The Stability of Rotating Liquid Masses", this could not have occurred by any reasonable physical process. Since this should occur due to an instability, as the body increased its angular ~~momentum~~ velocity the velocity imparted to the detached mass would have been sufficient to cause it to leave the earth-moon system. In fact it is likely to have been given a velocity large enough to carry it out of the solar system entirely.

Chandrasekhar has expressed the view that Lyttleton's calculations are probably correct and that the only reasonable answer is that the moon is a little chunk of material left behind when a larger mass was thrown off the earth by some cataclysmic action.

All things considered, if we eliminate this last concept, then the evidence favors the idea that the moon is more nearly like the sun in composition, certainly more so than like the composition of the groups of meteorites which have been used in recent years to estimate the so-called cosmic abundance of the elements.

Thermal History

Next we will discuss the thermal history of the moon. In this discussion we will limit the basic premise to that of an originally melted moon; actually it is presumed that the whole of the solar system was initially in a melted state. Since 1900, when radioactivity was discovered, such an assumption is unnecessary since adequate radioactive heat is known to be available in order to account for the observed high temperature processes.

If the moon as melted during its formation 4.5 billion years ago, the solidification which follows requires that the radioactive elements must be concentrated near the surface. Had the moon been formed cold then it may be necessary that the interior be melted now. As a matter of fact if this same hypothesis is applied to the earth, then assuming a uniform distribution or radioactive elements, equivalent to the surface concentration, the earth would have to be melted at present and from the time of its formation.

In regard to the heat generated by radioactivity some consideration of the more important nuclides is in order. Essentially these elements are potassium - 40, thorium and uranium, and are the components found in the chondritic meteorites. At the present time the total energy generated by these components is 1.6 ergs per gram per year. Assuming a specific heat of 1.25 joules per gram, the total heat generated by these nuclides in the chondrites in 4.5 billion years is 2330

joules per gram. This would provide a temperature of 1864°C, which is a considerable rise in temperature during this time period. Such a rise in temperature, of course, presumes no heat loss from the material. To account for this loss in heat one calculates the change in temperature due to surface cooling (for constant heat conduction and uniform heating by the radioactive components) from

$$\frac{\partial T}{\partial t} = K \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) + \sum_i Q_i \, e^{-\alpha_i t}$$

where T is the temperature, t is time, K (=k/ρc) is the thermal diffusivity. Here, too, k is the (constant) thermal conductivity, ρ is the mean density, and c is the specific heat of the material. The summation is taken with respect to the "i" nuclides present; Q_i is the temperature rise rate of the ith nuclide at t=o, and α_i represents its decay constant.

In order to solve thisequation one must assume an initial temperature. It will be assumed that the moon accumulated in a cold state, and an initial temperature of 0°C will be chosen. Having ascertained that heating occurs due to radioactivity a brief look at the conditions of melting is in order.

The silicate materials making up the moon do not all melt at the same temperature. That is, some constituents begin to melt at one temperature with final melting occuring at some higher temperature. On the assumption that initial melting begins at 1100°C and final melting occurs at about 1600°C (at a standard temperature and pressure), and that the melting temperature varies with depth

of material (that is, with pressure), then the following formulae are proposed

$$T_i(^oC) = 1100 + 500\ (1 - \frac{r^2}{a^2})$$

and

$$T_f(^oC) = 1600 + 200\ (1 - \frac{r^2}{a^2})$$

where T_i and T_f are the initial and final melting temperatures respectively. According to these expressions initial melting begins at about 1600°C at the center of the moon (r=0) and final melting occurs there at about 1800°C. The above formulae are to be used for estimating the melting within the moon due to radioactive heating.

Now let it be supposed that the moon formed as a completely melted body. In this case solidification occurred from the center outward and the more dense materials, having the higher melting point, would crystallize and sink to the center. Presumably this would be olivine and metallic iron. As solidification continued the lighter components would rise toward the surface and finally solidify at about 1100°C. For the case of a recently melted moon which solidified from the center outward it is assumed that the temperature through the moon follows the formula

$$T\ (^oC) = 1100 + 900\ (1 - \frac{r^2}{a^2})$$

Hence the temperature at the center of the moon would be about 2000°C while the surface temperature would be at 1100°C.

Returning now to the cooling history differential equation it can be shown that a solution is obtained in three terms, each of which is itself an infinite

series. The first part of the solution (T_1) shows the influence of the radioactive heating. The second term (T_2) is the cooling from an initial thermal state, at temperature (T_o) throughout; and the last term (T_3) is a consequence of the quadratic temperature variation through the moon itself. The three expressions referred to are:

$$T_1 = \frac{2a}{r} \sum_i \sum_{n=1} \frac{Q_i}{\alpha_i - K \left(\frac{n\pi}{a} \right)^2} \frac{(-1)^n}{n\pi} \sin \left(\frac{n\pi r}{a} \right) \left\{ \exp(-\alpha_i t) - \exp\left(- \frac{K n^2 \pi^2 t}{a^2} \right) \right\}$$

$$T_2 = - T_o \frac{2a}{r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n\pi} \sin \left(\frac{n\pi r}{a} \right) \exp \left(- \frac{K n^2 \pi^2 t}{a^2} \right)$$

$$T_3 = - \Delta T \frac{12a}{r} \sum_{n=1}^{\infty} \frac{(-1)^n}{(n\pi)^3} \sin \left(\frac{n\pi r}{a} \right) \exp \left(- \frac{K n^2 \pi^2 t}{a^2} \right)$$

The value of Q_i in T_1 can be calculated from the equation

$$Q_i = \frac{E_i}{c} \alpha_i m_{ip} \exp(\alpha_i t)$$

where E_i is the specific energy of the ith nuclide, m_{ip} is the mass of the ith nuclide per gram of meteorite material at the time in question (say 4.5 billion years) and c is the specific heat of the meteorite material, assumed constant at 1.25 joules per gram. All other terms in these expressions have been defined previously. Values for the Q_i have been calculated and are available in the literature.

The calculations on the temperatures within the moon depend markedly on the concentrations of potassium, uranium and thorium in lunar material. As explained in the footnote, this problem has caused great confusion during the last ten years or more. At the time that Chapter 13 of "Physics and Astronomy of the Moon" was written, i.e., 1959, no very reasonable estimate of these concentrations different from that of the chondritic meteorites was recognized. Since then, it has become evident from studies on the concentrations of rare elements in the carbonaceous chondrites that these objects contain the rare elements in more nearly the concentrations expected from studies of atomic abundances and the theories of nucleogenesis than do the ordinary chondritic meteorites. (See Goles and Anders (1962) and references there cited.)

The concentrations of potassium in the carbonaceous chondrites is not constant and varies from 380 to 750 ppm (Edwards and Urey, 1955; Edwards, 1955) with an average of 528 ppm instead of 863 ppm which is the average of the chondrites. A small systematic error is probably present in the analytical data and the latter average was lowered to 823 ppm, which seems to be a reasonable correction. For the same reason the average of 528 ppm may be too high and the true value may be considerably less. We will use 500 ppm and there is considerable probability that the true average will not be lower than 400 ppm for this quantity. Adoption of this latter value would lower temperatures by a maximum of 178°C beyond those given below. The concentrations of uranium and thorium are much the same in the carbonaceous and other chondrites. Values secured recently are about 25 per cent higher than those used in the calculations in 1959 as given in the above paper. This increase would raise the maximum temperatures due to uranium and thorium by about 100°C. Such a revision in view of the many uncertainties in

concentrations, specific heat, thermal conductivity, initial temperatures, etc., is not justified.

Table I and Figures 2 and 3 give the results of revised calculations for the cases of the intially hot and cold moons using 500 ppm for the abundance of potassium.

The present estimates of lead-lead ages for the meteorites run somewhat higher than the 4.5 AE used in the calculations, and revision of the curves for this effect would raise the curves slightly and extend them beyond 4.5 AE ordinate as given in the figures.

It is evident that lower lunar temperatures than have been calculated previously are possible and even probable, and in this case a more rigid moon at a temperature below the melting point of meteoritic iron-nickel is possible, providing that the initial temperature was not much above $0^{\circ}C$.

From the curves presented it is apparent that in the deeper interior the temperature has accumulated in time, while nearer to the surface the temperature has risen to a peak value and subsequently cooling has produced a small decrement over the last 2.5 billion years (approximately).

MacDonald has carried out machine calculations similar to those shown here and has results which have the same graphical shape. His results differ a bit from those shown here in that his initial lunar temperature was $600^{\circ}C$, and he has included a radiative transfer term in his calculations. Too, MacDonald has calculated the change in radius with time, due to heating, which has not been done in the present studies.

Next consider the question, could the moon have been completely melted from the time of its formation? In this case, the surface temperature would have

started at about 1100°C and cooled throughout its history. Of course the same situation exists for all radial stations within the moon, but with more rapid and a greater degree of cooling being apparent near to the surface. At the center of the moon very little cooling will have occurred during the 4.5 billion years of its existence through diffusivity (See Figures 4 and 5). The variation of temperature with depth (or radius) follows the quadratic variation given previously. These graphs do not consider any radioactive effects whatsoever. Should there be any radioactive heating in the interior, then the temperature will necessarily be increased. One might expect to find temperatures of the order of 2500°C to 2800°C, as a maximum, dependent on the choice of potassium abundance.

Now a discussion of how this applies to the irregular shape of the moon is in order. The moon's irregular shape is due to bulges toward and away from the earth. These bulges are estimated to be about one kilometer in height, whereas the equilibrium height of the moon would be about 60 meters. (The 1 km datum comes from the dynamical characteristics of the moon's orbit and is expected to be a rather reliable figure). Hence, the bulge could be accounted for by assuming the moon has had a certain rigidity for quite some time and could support this irregular feature from a time in its early history.

Now to define this situation, I suggested to Professor Elsasser that probably in its accumulation the moon acquired a variation, with angle, in the concentration of high density material. If this occurred the highest density material would be located in the polar regions of the moon and the lowest density located in the direction of the earth-moon radius vector.

For this case we are able to account for the irregular shape of the moon regardless of whether the lunar interior is rigid or not. Of course it should

be recognized that any angular density variation such as this could not exist unless the moon was formed as a low temperature body; certainly this could not be so if it has been melted at any time in its history.

There is a new suggestion, recently put forward by Dr. Runcorn, namely, that the moon is a convecting moon. Runcorn has suggested that convection in two cells occurs with rising currents toward and away from the earth and sinking currents at the limb. The rising currents should be hotter than the sinking currents and hence there should be a difference in density. In this way the explanation of Urey, Elsasser and Rochester (1959) for the dynamical bulge of the moon is accounted for without postulating differences in chemical composition between regions along the axis toward the earth and the limb regions. This is a most intriguing suggestion.

Much evidence exists for convection within the mantle of the earth. Possibly the most convincing of such evidence is that from the magnetic anomalies in the Pacific Ocean off the coast of California as investigated by Vacquier, Raff and Warren[8] (1961). Great blocks of the earth's crust, of the order of a thousand kilometers in dimensions, have moved relative to each other by hundreds of kilometers. No explanation for this seems to be reasonable except that the crust floats on and moves with great currents in the mantle below. Much older evidence for the phenomenon exists as well.

There appears to be no definite evidence for such convection cells in the lunar surface features. It is true that there are easily recognized fissures in the central regions of the visible hemisphere which are not of a concentric character about the center of the lunar disk as might be expected on this

hypothesis and, in fact, the present writer has maintained that this argues against lunar convection cells. If such cells exist, the lunar surface must be sufficiently rigid now and must have been so since the surface features were formed to resist effective deformation by the convection cells, such as is now occurring in the earth's surface. As argued previously, there is other evidence for a very rigid and thick outer region of the moon. This outer region is much thicker and more rigid than the outer regions of the earth.

Chandrasekhar (1953) has studied convection in spheres and has discussed convection in the earth. He found that the single cell convection should be stable in a sphere without a core and as the core formed and grew that two, then three etc., cell convections should become stable. The two cell convection should become stable when the radius of the core was slightly less than 0.2 of the radius of the sphere, i.e., just about that for the model discussed there. However, Chandrasekhar assumed uniform physical properties throughout, i.e., viscosity; hence his quantitative conclusions will not apply to a convecting moon. It is also very difficult to estimate what the proper boundary conditions for this object with a rigid outer shell are.

In spite of the difficulties and uncertainties present in this model, the history of the moon should be reconsidered in accordance with this explanation of the non-equilibrium lunar shape. It is still possible that the moon formed at low temperatures, that melted iron formed on the interior and formed a core during geologic times, and that now there exist two convection cells as discussed above. This model would account for the rigid outer shell without difficulty

and no new problems would arise. On the other hand, we may consider the possibility of a completely melted moon initially since the cool moon hypothesis was proposed only in order to account for its shape in some physically reasonable way.

If the moon were originally melted, it is necessary to consider the source of energy which melted it. Some years ago, the writer suggested that Al^{26} may have been present during the time of accumulation of the solid bodies of the solar system. This idea was not pursued and developed partly because of the difficulties in understanding the structure of the moon. Runcorn's suggestion removes this difficulty. It is immediately obvious from the calculations on the thermal history discussed above that the moon would melt throughout if sufficient Al^{26} or other short-lived radioactive nuclides were present in sufficient amount to produce melting, since no effective loss of heat by conduction would occur, for example, within some ten million years which is about 13 half-lives of Al^{26}. After it decayed, the moon would solidify from the center outward and cooling would proceed along the lines discussed in this paper.* In this case a core would form if elemental iron and nickel were present in the primitive material or if oxides of these elements were reduced by appropriate reducing agents, e.g., graphite or carbonaceous compounds.

There are some incidental advantages to this model. Kozyrev has observed the spectrum of C_2 in an emanation originating near the center peak of Alphonsus.

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* Fish, Goles, and Anders (1961) have discussed the cooling of small bodies of the size of the asteroids after being melted by short-lived radioactive nuclides. In the case of such small bodies, cooling during the heating process will be important and a simple discussion of the course of events is not possible.

Carbon vapor as such can be produced only at very high temperatures far beyond those required to melt silicate rocks. Also, it reduces the oxidized iron of silicate rocks at moderate temperatures and is oxidized to carbon monoxide and dioxide. Carbon vapor is not a constituent of volcanic gases for very well understood physical-chemical reasons. However, if the surface rocks of the moon were once heated at high temperatures (1800°C or higher) in the presence of graphite, with the possibility for carbon monoxide to escape, carbides, such as CaC_2, would be formed. Such compounds react with water to form acetylene, C_2H_2, which would be converted to C_2 in the presence of the ultraviolet light of the sun. In this way Kozyrev's observations become understandable (Urey, 1961). But this process required that at some time near surface materials were heated to high temperatures with the escape of carbon monoxide. This might be supplied by radioactive heating or possibly by heating due to an adiabatically compressed gas sphere (Brainbridge, 1962).

The high temperatures model is appealing due to this possibility. Of course, water must have been stored below the surface and must have been kept there throughout the history of the moon. The amounts required would be comparatively small and possibly it is unnecessary and not possible to specify the mechanism of retention in detail.

It is interesting that some meteorites contain elemental silicon or iron silicide and these compounds are produced from siliceous material and graphite under conditions almost identical to those required for the production of calcium carbide. It is not unreasonable to suppose that the moon and meteorites may have been subjected to similar conditions.

Now we will return to the question of the origin of the moon. In connection with this subject the best basic answer is that nothing is known on how the moon

originated, nor do we have any knowledge of how the solar system, as a whole, acquired its present configuration. However, evidence in regard to these questions does exist and it is quite possible to gain knowledge from a study of the available facts. Because of this it is interesting to review the problem of the origin and history of the moon, and in particular to look into the relationship it has with the earth and the solar system as a whole. Any information or conclusions reached on the basis of present information is subject to modification or change, as knowledge is gained from direct exploration of the moon in the future. One should always keep in mind that we do not know how the moon originated.

With this as an introduction, one of almost complete ignorance on the part of everyone, I will now tell you something about the origin of the moon.

All explanations for the origin of the moon are improbable. To mention one, consider the explanation as given by George Darwin; this, incidentally, has been disregarded by astronomers for quite some time. Lyttleton, from his studies, has reached the conclusion that there is no feasible way by which material could be gotten off the earth to form the moon.

Recently Dr. Donald Wise visited La Jolla and made a suggestion on the subject of lunar formation. He proposed that during the formation of the earth iron was present and became distributed throughout the body. As the body warmed up the iron sank to the center and, as a result, the angular velocity of the earth increased. This increase in angular velocity caused material to come off the earth which accumulated to form the moon.

This is an interesting idea but is contrary to the findings of Lyttleton. His finding is that if the angular velocity is increased, for a liquid body, the body

TABLE I

Present Temperature (°C) of a Cold Moon at 0°C 4.5 AE Ago

		K = 0.005					K = 0.010				
$\frac{r}{a}$		0.0	0.5	0.8	0.9	0.95	0.0	0.5	0.8	0.9	0.95
Initial Melting Temperature		1600	1475	1280	1195	1145	1600	1475	1280	1195	1145
Complete Melting Temperature		1800	1750	1672	1638	1621	1800	1750	1672	1638	1621
Temp. rise in 4.5 AE due to											
individual nuclide	K^{40}	888	874	640	365	190	888	806	449	238	119
	Th^{232}	132	131	101	63	36	132	123	79	45	24
	U^{235}	96	88	61	33	17	96	83	42	21	10
	U^{238}	174	170	133	85	47	174	160	99	57	29
	Total	1290	1263	945	546	290	1290	1172	669	361	182

Present Temperatures (°C) of a Moon Solidified 4.5 AE Ago

	K = 0.005					K = 0.010				
No radioactive elements in the interior										
Initial Temperature	2000	1775	1424	1271	1187	2000	1775	1424	1271	1187
Residual Temperature T_2	1098	1052	608	311	153	1071	872	392	189	91
Residual Temperature T_3	772	549	222	108	52	645	437	169	80	38
Total Temperature	1870	1601	830	419	205	1716	1309	561	269	129
With 1/2 of radioactive elements in the interior										
	2515	2232	1302	692	350	2361	1895	895	449	220

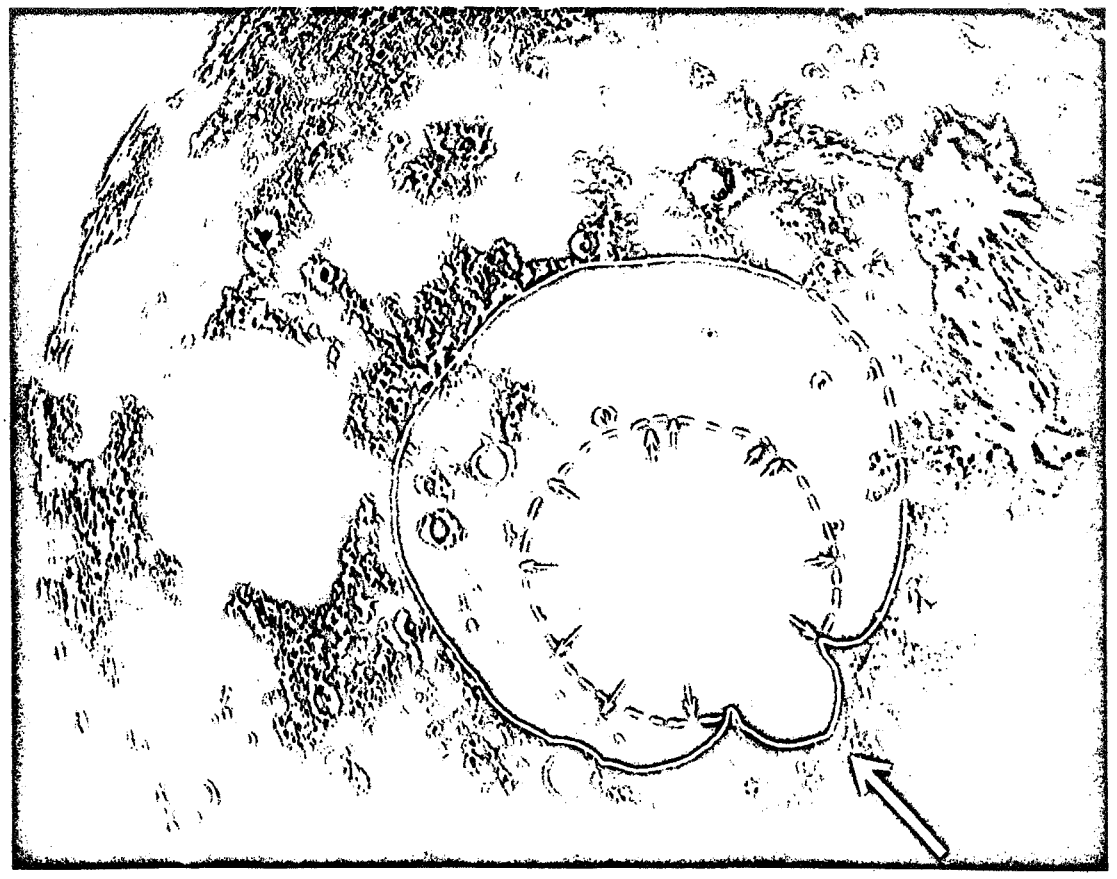

Figure 1
Mare Imbrium, with foreshortening eliminated. Mare Imbrium is outlined by the solid curve. Sinus Iridum is the bay at the lower right. The arrows indicate mountainous masses just outside the collision area. Three of these arrows point to masses not visible in this picture but easily seen on others. (University of Chicago photograph.)

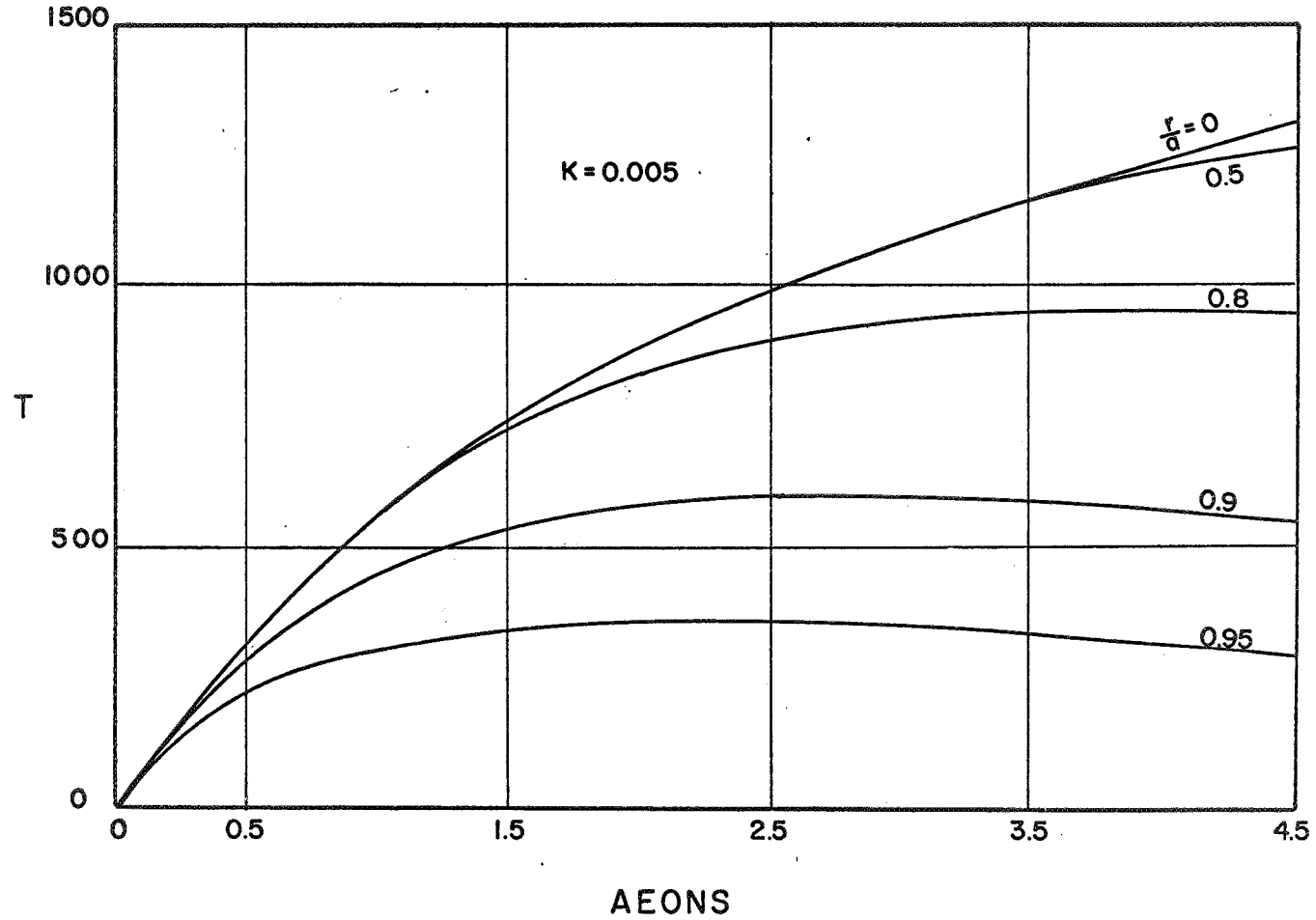

Figure 2

Temperature variation within the Moon, with time, for an initial temperature of 0°C, and for K = 0.005.

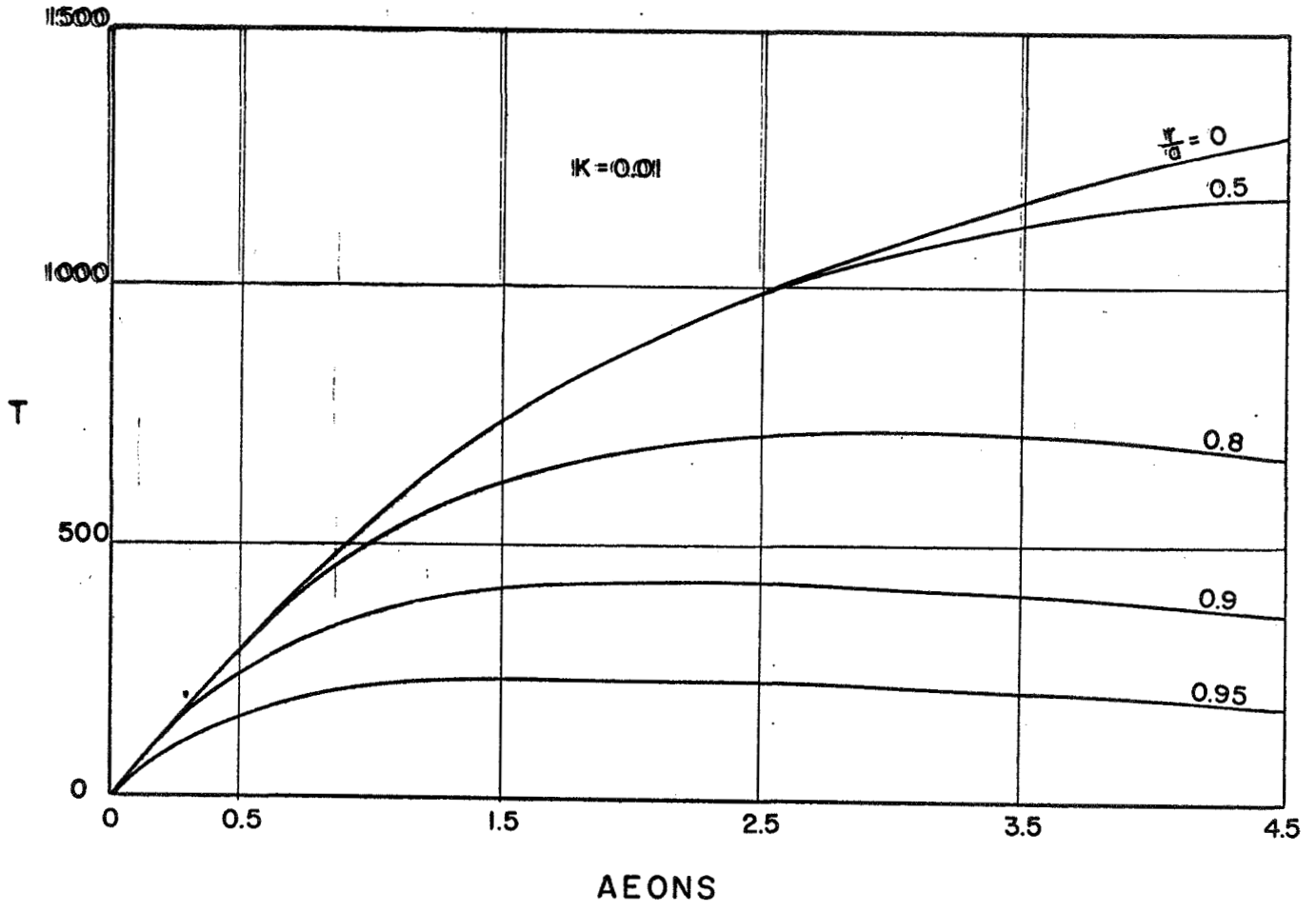

Figure 3
Temperature variation within the Moon, with time, for an initial temperature of 0°C, and for K = 0.01.

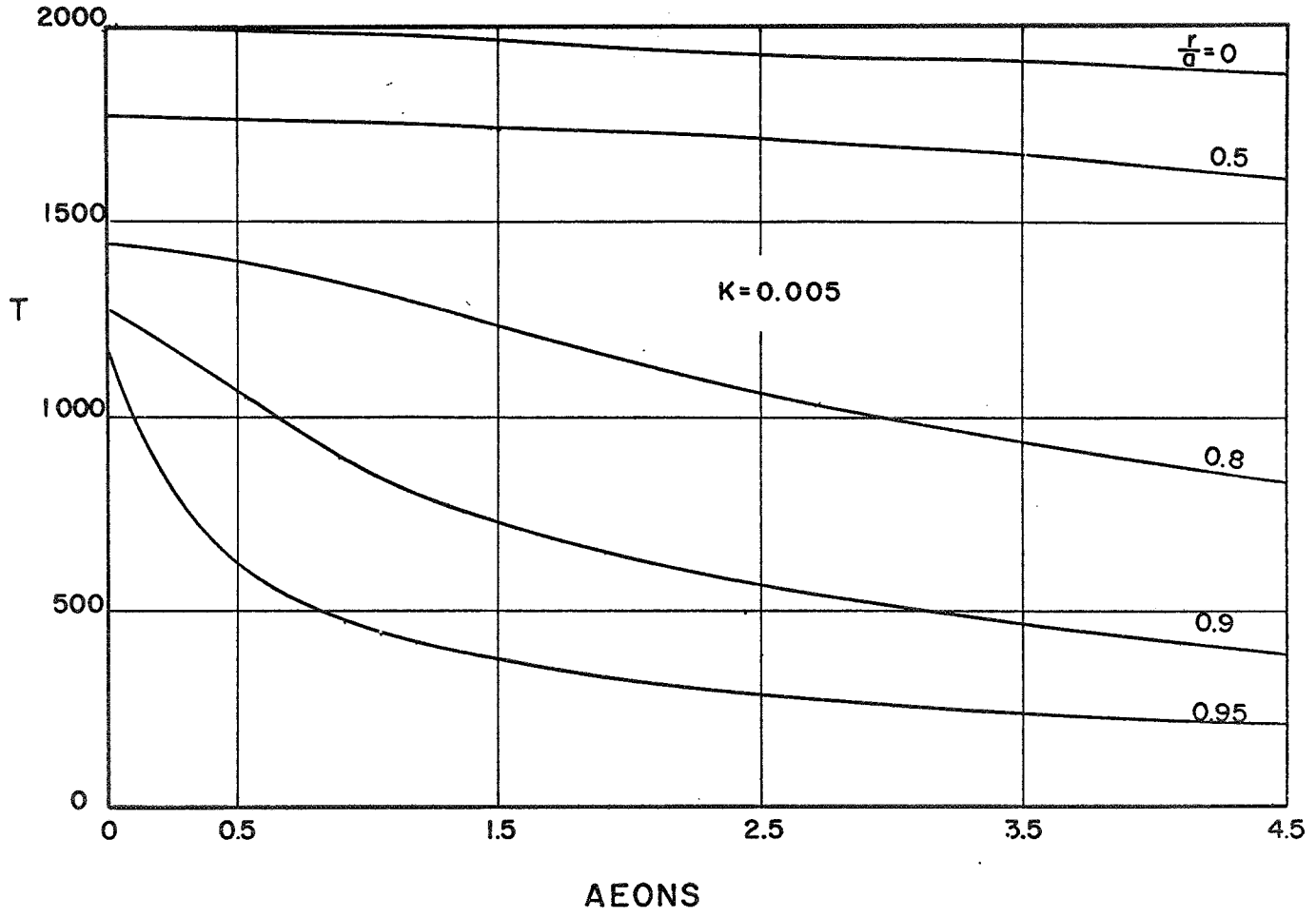

Figure 4
Temperature variation within the moon, as a function of time, for a moon completely melted at formation.

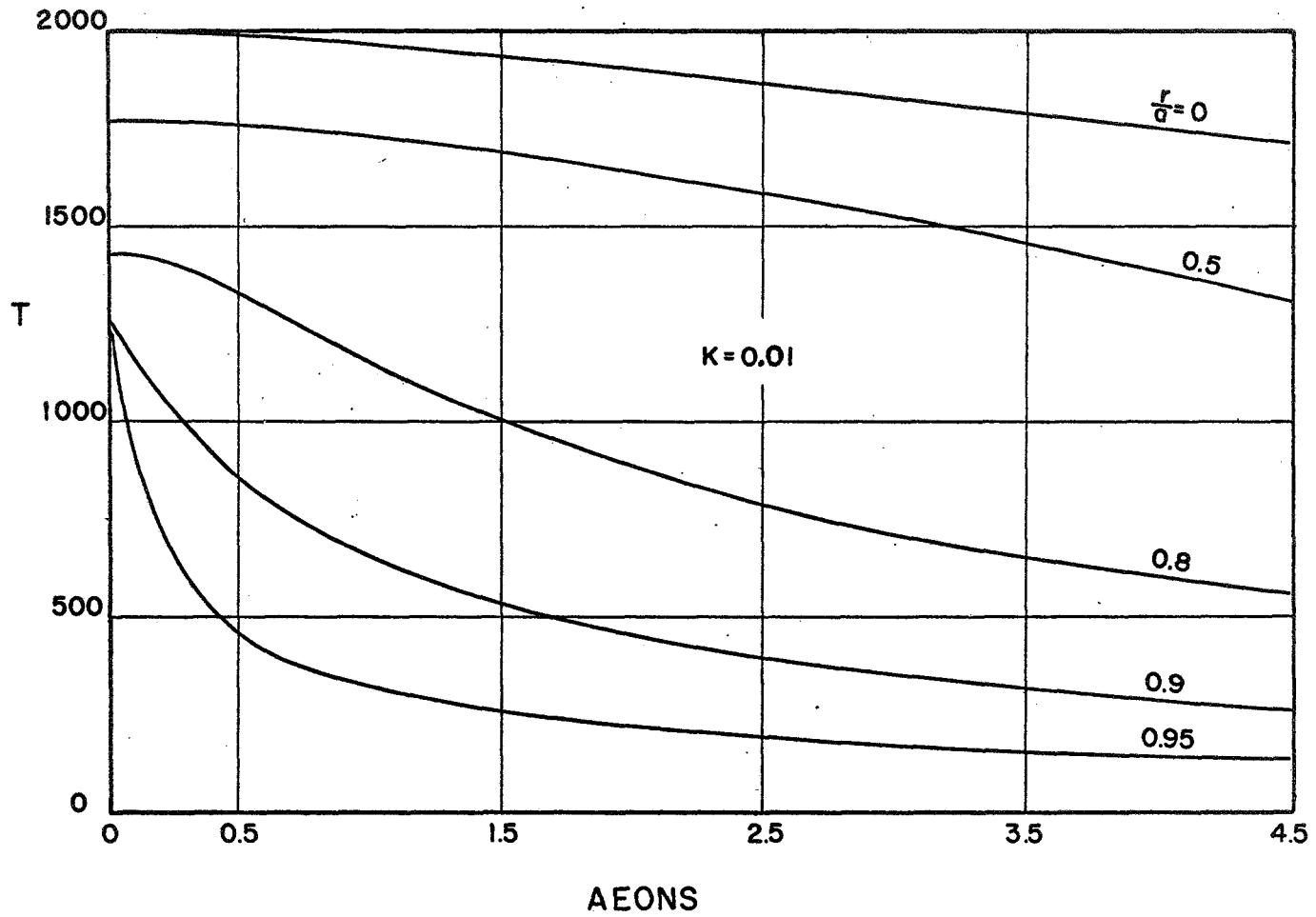

Figure 5
Same as Figure 4 except for the thermal diffusivity, K.

STUDIES OF THE LUNAR SURFACE I

flattens from an oblate spheroid to a disk, with no material being spun off its edge. Hence the suggestion of Dr. Wise does not seem to suffice.

Another idea for formation is that the earth and moon accumulated in the same gas cloud. For this case it is difficult to understand why they have different chemical compositions.

The author has suggested another method for the accumulation of the moon. Suppose at some time there was a solar nebula; how it got there will not be discussed. We merely assume it was there at one time. Now the question is asked, "What instabilities might be expected?" Conveniently a formula for such has been derived, by Dr. Schatzman, Dr. Chandrasekhar, and others. In the present case one would expect that the vast nebular disk of material would break up by gravitational instabilities. Next we ask, how large the objects formed would be. This all depends on the density and temperature of the material. The formula for the masses of objects formed is

$$m = \left(\frac{RT \gamma \pi}{\mu G} \right)^{3/2} \frac{1}{\rho^{1/2}}$$

where γ is the ratio of heat capacities of the gas, μ is the molecular weight, G the gravitational constant and ρ a density of the gas. Regarding the temperature, it was assumed to be rather low; as for density, let it be assumed to be 2×10^{-6} divided by the third power of the distance from the sun (in astronomical units). This is the density at which a gaseous object would stay together under its own gravitational attraction in the gravitational field of the sun. For temperature the author has used a temperature low enough to keep the nebula at a relative small size. Since the temperature enters into the formula raised to

the three halves power, then as the temperature increases the mass of the nebula also increases and its size does likewise. A result of the calculation, with these assumptions, is that one obtains lunar sized objects in the neighborhood of the terrestrial planets, or objects slightly less than lunar size,i.e. of lunar mass plus the proper proportion of gases. As one moves outward in the system the object sizes increase until they are about ten times as large as the moon at a distance equivalent to the position of Neptune. This suggests a mass of gas and dust of about the right size to produce lunar objects. Of course the material should collect inside the gaseous mass to form a silicate object near its middle. Thus we now have a way for material of cosmic composition to accumulate.

Now, if a moon was captured by the earth, then this is a most improbable capture. It should have come into position along a hyperbolic orbit, had collisions to dissipate some of its energy and then not quite escape. This all is highly improbable; however, if a large number of moons existed at one time in the solar system then the improbability of a capture is not so remote.

If the moon was captured by some such scheme, then it is possible that there could have been a large number of moons in the solar system at one time. I have calculated how long it would take such objects to collide with one another after losing this gas mass which surrounds them. On the basis of equal partition of energy these bodies would be moving in and out and up and down relative to the sun, and they would collide. It is supposed that they would interfere with one another by various processes. Part of the silicate material associated with such bodies would be blown into space along with the gases, leaving behind a residue of

more dense materials such as iron and nickel; these residues would then accumulate to form the terrestrial planets. The moon is an object which by accident escaped destruction and was captured by one of the terrestrial planets.

Of course this whole scheme of origin is also improbable and as stated previously, all proposed schemes of origin are likewise improbable. If one does not care for any one or more of these suggestions, he should recognize that they are all improbable and equally subject to supposition and fallacy.

Very extensive areas of disagreement in regard to the structure and history of the moon exist in the minds of many thoughtful students of the subject. Only more detailed evidence can clear up these areas and lead to general agreement.

Specifically, the lunar exploration program should give us further data in regard to the distribution of mass within the body of the moon, the number and intensities of seismic events, and the chemical composition of the surface regions. The concentrations of potassium, uranium and thorium can be determined by radioactive detection devices flown above the surface. If these concentrations are low as they are in the meteorites, then extensive differentiation by melting processes as is characteristic of the earth has not occurred. Such investigations should be interpreted with caution because the surface may be somewhat different from regions immediately below. As Shoemaker (1962) has shown, many blocks of material have been thrown about over the surface by the great collisions, and if men visit the moon and are sufficiently experienced in hard rock geology, they will be able to pick up many varieties of such rocks, if indeed these varieties exist; much valuable information in regard to the surface composition will be secured in this way. We need to have such scientific people among the astronauts who first land on the moon if the Apollo project is to be of maximum scientific value.

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A More complete discussion of the subject will be found in Chapter 13 of the "Physics and Astronomy of the Moon" Editor, Z. Kopal, Academic Press (1962).