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Chapter 3

THE MOON AND ITS NATURE

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The Moon and its relation to the Earth and Sun have been observed by men from ancient times to the present with ever-increasing intensity and effectiveness. Results of these studies up to the most recent years have been recorded in numerous treatises and textbooks. For present purposes, it is not necessary to review the older work, which will be referred to without detailed discussion whenever it bears on very recent work.

The lunar surface consists predominantly of many craters produced by great collisions. This applies particularly to the far side and the terrae areas of the near side. The great circular maria, Imbrium, Serenitatis, Crisium, Nectaris, Humorum, and Orientale, were produced by great collisions; the shallow, irregular maria consist of flooded areas with igneous materials over previous terrain similar to the terrae areas. These shallow maria have mountainous masses protruding through the dark, smooth material, and may cover areas that are collision maria, the outlines of which have been obscured by subsequent events. If such collisions have occurred on the Earth, which appears to be a necessary conclusion, all Earth rocks laid down prior to this collisional history would have been converted to rubble. Since well preserved igneous and sedimentary rocks are preserved in the Earth's surface from some 3.5 aeons ago, these numerous collisions must have occurred before that time. The ray craters, many smaller ones, and some larger craters without rays, have surely been formed during all geologic time. The great maria have the appearance of lava flows, ash or ignimbrite flows, or lakes of water. They certainly are not the last, shown by absence of water in the lunar rocks, but the choice between the others remains open. There are also explosive craters of internal origin and it is sometimes maintained that some caldera exist on the Moon. This writer has doubts in regard to the presence of any large caldera. Recent work is reviewed somewhat in the time sequence of discovery and study.

The physical constants of the Moon and its orbit are well-known, some of which are listed in Table 1.

GRAVITATIONAL FIELD

The gravitational field of the Moon has been investigated in great detail using orbiter satellites [37, 42, 43]. This field can be represented by the usual series in spherical harmonics only with the use of many terms; Michael et al [42] have given

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the most comprehensive tables for constants in the equation

$$V(\mathrm{r}, \phi, \lambda) = \frac{GM}{\mathrm{r}} \left\{ 1 + \sum_{n=2}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{\mathrm{r}} \right)^{n} P_{n}^{m} (\sin \phi) \right. \left. (C_{n,m} \cos m\lambda + S_{n,m} \sin m\lambda) \right\} \quad (1)$$

where r, ϕ, λ are the polar coordinates. They show that terms to the 13th order are necessary to describe the field, and even then, the constants are not decreasing, indicating that the field of the Moon is far from that expected for a weak body under gravitational forces of the Earth, Moon, and Sun and the centrifugal forces of rotation. In this latter case, the terms beyond $C_{2,0}$ should be zero, but this is not true. It must be concluded that some very irregular distribution of mass exists within the Moon.

The values of the constants

$$\alpha = \frac{C-B}{A}, \quad \beta = \frac{C-A}{B}, \quad \gamma = \frac{B-A}{C}$$

where A, B, and C are the moments of inertia, A about the axis pointing to the Earth, B that about the east-west axis, and C that about the polar axis, have been carefully studied by Koziel [29] who gives 3.984, 6.294, and 2.310, all $\times 10^{-4}$ for these constants from lunar librations. Kopal obtains similar values for these constants [27]. The calculated values for a plastic Moon under tidal and centrifugal forces are 0.94, 3.75, and 2.81, all $\times 10^{-5}$. Again, these constants indicate that the Moon is a very rigid body and has been since early in its history. Estimates of moments of inertia have been made, indicating that these moments are close to $0.4\,Ma^2$, where M and a are the mass and radius of the Moon. This value is characteristic of a sphere with uniform density throughout. The surface regions, for some depth, must consist of low-density material and should lower the moments of inertia to some extent. This low density is located predominantly on the far side—possibly 30 km thick—and is responsible mostly for the Moon's irregular shape, moments of inertia, and displacement of the center of mass relative to the center of figure—2 to 3 km [26].

TABLE 1.—*Physical Constants of the Moon*

Mass	7.35×10^{25} g
Radius	1737 km
Surface force of gravity	162 cm/s^2
Orbital mean radius	384 403 km
Orbital eccentricity	0.05490
Velocity of escape	2.38 km/s
Sidereal month	$27^{\cdot d}$ 32 166

The triaxial, ellipsoidal, nonequilibrium shape of the Moon is a puzzle of long standing, for which various explanations have been offered.

1. The Moon may be sufficiently rigid to support the irregularity, although this does not explain its origin.
2. The lower temperature at the poles should result in greater density material and smaller radii in these regions [35], but this does not explain the difference between the A and B moments of inertia.
3. Convection in the Moon in two cells rising at the poles and sinking at the Equator should give less mass at the poles and higher mass at the Equator [57], but again, the A and B moments should be equal. Possibly a special combination between the second and third suggestions is possible.
4. The Moon accumulated from objects of variable density which should give variations in moments of inertia [87]. If convection occurs, the Moon must have been melted greatly at some point in its history, since two-cell convection requires a small core, according to Chandrasekhar [12]. The convection must be deep enough in the Moon so that no folded mountains are produced, as on the Earth. Booker [8] proposed a single-cell convection which may have produced the higher level of the far side if the rising current was in the region of the near side.

Anomalies

Muller and Sjogren [44, 45, 46] showed that substantial mass concentrations, called mascons, exist in various locations on the near side of the Moon which are associated mostly with the circular collision maria and probably always where definite localized masses occur. The mascons were discovered and mapped by observing flights of the orbiters and measuring their velocities directly. Muller and Sjogren believe that the observations are reliable for longitudes between 100 and −100° and latitudes between −50 and 50°. The marked positive gravity anomalies in Maria Imbrium, Serenitatis, Crisium, Nectaris, and Humorum are evident, as is a positive anomaly slightly to the northwest of the center of the lunar disk. Mare Orientale appears to have an anomaly which is partly positive and partly negative. Other positive and negative anomalies are probably within observational error. A negative anomaly in Sinue Iridum is regarded as real by the authors. They also noted negative anomalies in Ptolemaeus and Albategnius of some 87 milligals (mGal) from observations of the Apollo 12 flight in its approach to the landing site. Booker et al [8] estimated the excess masses required to produce the observed anomalies of the order of 10^{21} G and produce excess pressures below these masses of about 100 bars. Since all these features are very old, the gravity anomalies have been supported by the Moon for several aeons, indicating that it has, and has had, very high rigidity.

Two distinct classes of explanations for these effects have been offered. (1) It is presumed that material from the lunar interior has risen by various processes into excavations produced by the objects which produced the maria [7, 25, 48, 95]. (2) It is suggested that the mascons consist of remnants of the colliding objects themselves, together with substantial material filling the excavation produced by the collision [27, 67, 85, 88].

If lava flows from the interior are responsible for the mascons, it must be possible to account for the excess pressure required to produce these deposits, i.e., about 50–100 bars. No satisfactory source of such pressure exists. Possibly material has flowed into the great excavations, produced by large colliding objects from surrounding areas. Probably Van Dorn's [90] great waves in a highly fragmented surface layer of the Moon would bring this about, but special assumptions are necessary to account for the excess mass per unit area. If lava flows from beneath neighboring areas into the mare regions occurred, the excess mass might be explained. Sjogren concluded recently that the extra mass of Mare Serenitatis consists of a near surface slab which may have been produced by such lava flows.

Another assumption is that the interior rocks of the Moon moved as solid material into the great cavities produced when the maria were produced, and that these rocks were of higher density than the rocks more on the surface. If they moved until reaching isostatic equilibrium, no gravitational anomalies would be observed, but if they did not quite reach this position, negative anomalies would be observed. If the rocks exceeded this, due to high momentum of the rising material or fill-in over the mass by lava flow or fragmented materials, there would be a positive anomaly, as observed. In this case, great strength in the highly broken material below must be postulated, which may be possible but does not seem probable.

It has been suggested that the outer parts of the Moon have considerable tensile strength, and that the heating within the Moon produces liquid that is forced up into the basins of the maria [25]. Such partial melting on Earth produces rocky materials which are less dense in the solid state and even more so in the liquid state than the rocks from which they are produced. On Earth, lava flows produce mountainous masses with positive gravity anomalies; on the Moon, these occur in the low-lying maria. Possibly the high-density titaniferous basalt could supply such material. However, the many cracks or regular rills in the Moon's surface do not favor the view that an outer shell of great tensile strength exists.

These suggested origins require that a net throwout equal to a volume of the area of the maria to a depth of some 50 km existed, and this requires a throwout layer of one-tenth this thickness over an area of ten times the area of Maria Imbrium and Serenitatis, for example. This writer is quite unconvinced that this is true on the basis of available photographs.

The suggestion that the mascons are the residues of colliding objects is based on several assumptions: that the objects arrived at velocities not much greater than the lunar escape velocity; that collision energies extrapolated from those of atomic explosions can be applied to the lunar maria; and that the volume of the net throwout of lunar rock is equal to the volume of the colliding object. This explanation requires considerable "fill-in" of some kind. Because of the difficulty of supporting the mascons if the lunar interior is at melting temperatures, it is assumed that this material was filled in during the collision by processes of the type discussed by Van Dorn [90]. Significantly, there seems to be approximate agreement between the masses required to produce the mascons and the masses required to produce the maria. The great excess mass of the mascon of Mare Imbrium and of those of other maria and their persistence for aeons (probably 4.0×10^9 years), indicates that the Moon is now, and has been, much more rigid and at lower temperature than the Earth, which establishes isostasy in some 10^7 years. It seems that immense lava flows and very large movements of material from the interior beneath the maria are inconsistent with the support of these massive structures during several aeons.

The Apollo 15 laser altimeter showed that great differences in altitude of lunar surface areas exist. The near side areas are generally depressed by about 2 km, and the far side elevated relative to the sphere centered on the center of mass. Also, the deeper points observed so far are in circular maria, which means of course, that some especially high-density masses must lie below the surface in these regions. The irregular Van de Graff crater on the far side is also very deep, and one wonders if a mascon exists in this area (see [55]).

SURFACE

The lunar surface is covered by craters and extensive smooth areas. The craters are mostly of collisional origin, but some volcanic craters are surely present. The collisional craters vary in size from the microscopic to the great collisional areas of the lunar maria, i.e., hundreds of kilometers in diameter. They are of varying ages—a very dense covering of older ones possibly 4.0 to 4.6 billion years old and a sparse covering of those which have been formed during all of geologic time. These craters, which have been studied by many with regard to numerous details, are, however, mostly random events with little more to reveal about the history of the Moon. Ptolemaeus and Albategnius have negative gravitational anomalies of approximately 87 mGal [45], and thus show that these old craters were formed on a rigid Moon early in lunar history, and that this rigidity has persisted to the present. Unfortunately, it appears difficult to state exactly what temperature regime would be consistent with this fact. The larger craters have central peaks indicating that some rebound of the material below has occurred, or that some residue of the colliding object remains; probably the former is the correct explanation.

Volcanolike craters are present on the Moon. Certainly the halo craters which are surrounded by black areas and rows of craters along winding cracks are such. The Davy rill is nearly a straight line of craters which may be of internal origin, or collisional craters from an object such as a comet head which broke into many fragments due to effects of the lunar gravitational field. In many cases, it is difficult to state whether other smaller craters also belong to this class, much effort having been directed to this problem. Many of these craters have wide mouths as though they were produced by emission of gases. (Steam is the most prominent volcanic gas on earth! What were these gases on the very dry Moon? Did water react with iron somewhere below to produce hydrogen, or was it carbon monoxide or something else?) Definite localized lava flow structures are observed in several places, particularly in Maria Imbrium and Serenitatis. Also, the Marius Hills in the western equatorial regions appear to have definite volcanic features.

The great maria represent extensive eruptive flows, generally thought to be lava, but which may be volcanic ash or ignimbrite. Lava flows to the Earth's surface are regularly frothy, and such flows to the lunar surface, where at present at least a hard vacuum exists, should have this character even if there are fewer volatiles in these melts. Soils are observed at present which consist of finely divided crystalline and glassy particles in which sizeable crystalline rocks are imbedded. These rocks have some cavities with smooth walls which must have crystallized from a melt containing macroscopic bubbles of gas, with the appearance of having solidified at some depth beneath an insulating surface layer. The soil has been partly produced by collisions of micrometeoroids on the soil and rocks, although probably it is partially of ignimbrite origin as well [50].

The great shallow maria—Oceanus Procellarum, Tranquillitatis, Fecunditatis, and Nubium—do not show marked and consistent gravity anomalies. Hence, the flows are in isostatic equilibrium indicating that the material of the flows probably originated below the surfaces where they lie, or isostasy was established for masses over large areas on the surface but not for the mascons lying some distance beneath the surface. These dark materials must be very thick (up to several kilometers), since the collisional mountains present originally in these areas are largely covered by these flows. These mountains may have been partly shaken down by the violent collisional process which produced the circular maria, but deep pockets and shallow areas must be present in these maria. A popular hypothesis for many years has been that these dark maria are deep lava flows from the lunar interior, and this opinion remains popular today. However, the seismic data are so different from those observed on the Earth that it is necessary to postulate some marked differences in surface structures in order to explain these differences.

Substantial differences exist in estimates of the thickness of the regolith. Shoemaker et al [64] find evidence for very small depths, some 3 to 6 m, in the crater near the Apollo 11 landing site. Kopal [28] argues from the depths of the rills for some hundreds of meters depth and Seeger [63] from the structure of the Dawes crater suggests 1 km as the depth at this point. Gold and Soter [20] argue for a depth of fragmented material of 6–9 km. These estimates are for mare material. The intense collisional processes in the terrae regions must have produced a highly fragmented material, and of course, the terrae surfaces have been subjected to the same micro- and macrometeoroid bombardment as the mare areas since their formation.

The great circular maria were produced by massive collisions. Van Dorn [90] has applied wave theory to these collisions and, particularly in regard to Mare Orientale, found satisfactory agreement between calculated and observed radii of wavelike structures surrounding this mare and others, if a liquid layer 50 km deep is assumed. However, it cannot be presumed that a liquid was present 50 km deep, and at the same time, suppose that a rigid crust supporting mountainous masses existed. A highly fragmented layer of solid materials possibly would behave as an imperfect liquid supplying waves under high energy which "froze" as energy densities fell to lower values.

The far side of the Moon is more elevated than the near side by approximately 3 to 4 km, and the center of figure is displaced about 2 to 3 km away from 25° E longitude [26]. This probably indicates that the crust is some 30 km thick on the far side of the Moon, consists of minerals rich in CaO, Al_2O_3 and SiO_2, and contains little FeO.

The physical evidence for the lunar surface strongly favors the view that there is a substantial fragmented layer of silicate materials in the surface of the maria and highlands, that the body of the Moon is remarkably rigid to a considerable depth, and has been during most of its age.

SEISMIC OBSERVATIONS

Seismic instruments were landed on the Moon by the Apollo missions, and the information received proved of great importance for understanding the lunar interior [34, 71]. The first most striking observation was that the rate of decay of seismic signals was far less than for terrestrial signals. The lunar module of Apollo 12 was dropped at a velocity 1.68 km/s, an energy of 3.36×10^{16} erg, and at a distance of 73 km from the seismometer. A signal recorded rose to maximum value in about 7 min and slowly decreased until it was hardly detected 54 min later. When the third stage of the Apollo 13 was dropped at 2.58 km/s and an energy of 4.63×10^{17} erg, 135 km from the seismometer, a similar record was obtained, lasting for more than 200 min. If the velocity of sound were 6 km/s, the sound would have traveled 21 600 km or 6 times the diameter of the Moon within 1 hour. Both P-and S-waves, i.e., compressional and shear waves, were recorded. Similar effects have been observed more recently. Such results differ greatly from observations on the Earth, where the signals would have died out in a few minutes. Other weaker signals, quite similar, have been observed, which are believed due to meteorite collisions. Other groups of signals have also been received, where the detailed pattern of vibrations is repeated exactly, indicating that successive members of a group come from the same location on the Moon and travel in identical paths from their sources to the seismometers.

The waves and vibrational energy for long period vibrations appear to be confined to a very limited volume, probably a layer on the surface of the Moon, mostly in the immediate neighborhood of the source. Such slow attenuation is not observed on the Earth, and hence, important differences in the surfaces of the two planets must exist. The most obvious is the more highly fragmented character of the lunar surface and high vacuum, resulting in absence of gas in the fragmented rocks of the Moon. Both Oceanus Procellarum and Mare Tranquillitatis must have a highly fragmented layer similar to that of the highland underlying the dark soil and rocky layer of the maria. Latham et al [34] discussed this structure, and Gold and Soter [20] presented calculations using a model of dust layer some km in thickness with sound velocities increasing linearly with depth, and with reflections from the top surface of the maria. The two models are quite similar, if it is remembered that blocks of rocks smaller than the wavelengths would make little difference in the flow and reflection of sound waves. It is probable that sheets of solid silicates would not behave in a similar way.

Some signals are precisely repeated and cannot be ascribed to meteorites, hence, are indigenous; these are more frequent at perigee, therefore appear to be triggered by a tidal effect. Reflections from various masses and surfaces must occur, hence, extensive heterogeneities must be present. These moonquakes mean that mechanical or potential energy from some source is being dissipated as vibrational energy and heat. Several sources of such energy can be considered.

1. The mascons are settling into deeper layers.
2. The irregular shape of the Moon is settling into a more spherical shape.
3. The ellipsoidal shape of the Moon's orbit is becoming more nearly circular with a lesser major axis; this effect would be superimposed on other changes in orbit due to other causes.
4. Convection in the lunar interior or lava flows cause terrestrial-type quakes.
5. As the Moon moves away from the Earth due to tidal effects, it keeps the same face toward the Earth, its velocity of rotation decreases, and this probably requires moonquakes, the decreased rotational energy supplying the energy.
6. Slight contraction or expansion occurs due to changing temperature of the Moon.
7. Rocks are falling from cliffs; however, it would seem probable that this would have been completed after billions of years.

These moonquakes appear to come from depths of some 800 km, and slight reflections come from similar depths indicating that some layering exists at these depths. However, definite evidence for a metal core has not been observed as yet. There appears to be a layer below the 20-km regolith or basaltic layer to 60-km depth having a compressional sound velocity equal to that of anorthosite, and below this material, to an undetermined depth, having a sound velocity of dunite. Thus, the layering seems to be approximately 20 km of fragmented basalt, 40 km of anorthosite, and then dunite to an unknown depth with a source of moonquakes and slight reflection at some 800-km depth with no evidence as yet for any metallic core. However, later data indicate that there is a central region which will not transmit S-waves, probably consisting of partially melted silicates. This central "core" has a radius of about 700 km [31].

The Moon is much quieter than the Earth which has immense sources of energy, the most important being convection in the mantle driven by radioactive heating. This builds the immense mountain chains, great gravity anomalies both positive and negative, produces the great volcanoes and lava flows, and moves the continental masses over the Earth's surface. If convection occurs (or has occurred) in the Moon, it must produce very minor effects compared to its effects on Earth.

The explanation of the seismic effects, due to a fragmented layer on the surface, argues strongly against a conventional bed of solidified lava below the surface. But there are rocks scattered in the soil which were produced by a melting process, and the complicated and detailed patterns from the moonquakes indicate that complicated structures exist below the surface.

CHEMICAL COMPOSITION

The most recent values for the radius of the Moon give a mean density of 3.36 g/cm^3, and the highly fragmented character of the surface suggests that the fraction of voids may not be negligible when estimating the density for the whole Moon. Also, the interior density may be lowered more by high temperatures than it is raised by high pressures. Again, this suggests higher true mineral densities at laboratory temperature and pressure; possibly 3.4 g/cm^3 is a reasonable estimate for the average of this quantity (see [88, 93]). Mean densities of chondritic meteorites of the L and H types under low pressures run about 3.57 and 3.76 g/cm^3 [86] or 3.68 and 3.85 g/cm^3, if high density minerals are present. The Earth's density at low temperatures and pressures may be about 4 g/cm^3.

The Moon contains either less iron or larger quantities of water and carbonaceous compounds than the Earth. The low concentrations of water and carbon compounds in the surface materials dispute the second hypothesis. Silicate minerals observed in meteorites with iron content limited to some 10% by weight would give the required estimated density. Carbonaceous chondrites Type III also have this density. The concentration of potassium is lower in these meteorites than in other chondrites, i.e., about 360 instead of 850 ppm. This lower abundance of potassium and comparable abundances of uranium and thorium would permit an initially cool Moon to remain below the melting point of silicates during geologic time.[2]

In a very thorough paper that reviewed the chemistry of the Moon [91], the conclusion was that the Moon's surface materials can be regarded as a mixture of two components: one condensed at high temperature, and another of average meteoritic composition. The ratio of K to U is about 2000, whereas this ratio in chondritic meteorites is about 60 000 or 90 000 due to greatly increased concentration of U and other high-temperature condensing elements. This ratio for Earth rocks is about 10 000 indicating that the Earth also has an increased high-temperature condensate fraction.

The first observational data on lunar composition were obtained in Surveyor flights 5, 6, and 7 [73, 74, 75, 76], showing that the maria contained basalt with high titanium content, and the highlands contained high concentrations of aluminum, calcium, and low concentrations of iron. These results were completely confirmed by the precise measurements on returned Apollo samples. Several distinct types of siliceous materials are on the lunar surface. The maria areas appear to consist mostly of basaltic-type rocks and finely divided material. The highland areas consist of rocks having high concentrations of calcium feldspars, so-called anorthositic-type materials. Then the area near Fra Mauro where Apollo 14 landed consists of so-called KREEP, high in potassium, rare earths, and phosphorus. No meteorites of the anorthositic or KREEP type have been observed, nor has any other rock type been exactly duplicated by meteorites. Other rock types found are apparently rare. Certain marked chemical differences exist between lunar terrestrial and meteoritic materials.

One very curious chemical difference concerns europium, an element which is divalent under highly reducing conditions and trivalent under less reducing conditions. In the lunar surface rocks, it has a strong tendency to follow the divalent strontium and decreased tendency to follow the other trivalent rare earths. This indicates that the lunar surface materials were formed under rather highly reducing conditions. Only small bits

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[2] In a recent paper, Tozer [72] discusses convection in planetary objects and points out that much greater cooling might occur in the Moon than would be expected if thermal conduction only was effective.

of metallic iron-nickel are observed, and it is uncertain whether these are native to the Moon or are fragments of meteorites. Iron sulfide is present only in small amounts; titanium contents, strikingly, are much higher in some lunar basalts than in terrestrial basalts.

The physical condition of these siliceous materials is of interest: the basaltic soil consists of finely divided crystalline and glassy chips, and the breccia appears to have the physical structure of sintered soil. Rocks are present which crystallized from a liquid melt, which sometimes contain smooth bubbles, indicating that gas was present when they solidified. The "genesis" rock 15415 consists entirely of glass spherules of calcium feldspar. The lunar materials often contain rounded silicate objects which are physically similar to chondrules of meteorites, but of different chemical composition. Only a few recognizable bits of meteorites have been observed, indicating that meteorites which must have fallen on the Moon have been broken into very small fragments. One or 2 percent of the lunar surface is of meteoritic composition.

Since the Moon has no atmosphere, it is possible to observe the high-energy radiation emitted by radioactive elements, i.e., rays at great heights above the lunar surface. Such observations were planned by Arnold very early in the lunar space program, and have recently been successful on Apollos 15, 16, and 17 [5]. These studies show that the maria areas have higher concentrations of K, U, and Th than have the terrae areas, also that there is some variation in concentrations of these elements over considerable mare areas. Also, the K/U ratio is considerably less in all areas than in terrestrial rocks. These results confirm analyses on returned samples, showing that the chemical differences apply to great areas of the Moon.

The study of fluorescent x-rays emitted by the lunar rocks under bombardment of solar x-rays showed the highland areas to be generally high in elements of anorthositic-type rocks [2]. Unfortunately, there are not more such detailed and extensive studies of the Moon.

Continuous melting of some kind on a limited scale appears likely from the earliest years of lunar history until about 3 aeons ago. The small lava flows reported at various locations may be more recent. If they come from the deep lunar interior, they may provide information regarding the chemical composition of the Moon's deep interior, which will be very informative. It was thought that Apollo 16 which landed near Descartes would find more recent volcanic materials, but this area proved to be covered with ancient anorthositic-type rocks and soil. The landing area of Apollo 17 near Littrow was carefully planned to be a recent lava flow area, but proved not to be so. At present, there is no evidence for more recent lava flows. It was hoped that Apollo 17 would provide examples coming from the deep lunar interior, but this proved not to be true.

CARBONACEOUS MATERIALS

Evidence for living or fossil forms on the Moon has not been found. The total concentrations of carbon in all lunar samples range from about 30 to 230 ppm, the concentrations in the soils ranging higher than in the crystalline rocks. Nitrogen concentrations are somewhat less.

Evidence was obtained for carbon-hydrogen, carbon-hydrogen-oxygen, and nitrogen compounds, but generally in such low concentrations that it is difficult to be certain that these are indigenous and not due to terrestrial contaminations. The gas chromatograph and mass spectrometer are so sensitive that contaminations in the range of parts per 10^9 of some compounds can be detected.

In general, all investigators found many carbon-hydrogen compounds containing up to some six or more carbon atoms and the more common and simple compounds of carbon with oxygen, hydrogen, and nitrogen. The more interesting compounds suggestive of those commonly present in living organisms were observed by a few. Nagy et al [47] reported glycine, alanine, and ethanolamine in addition to urea and ammonia. Glycine and alanine in nonhydrolized water extractions were reported, as well as glutamic acid, aspartic acid, serine, and threonine in extracts after hydrolysis. Amounts were in the range of 50 parts per 10^9 [17]. Porphyrin, while reported [24], was believed due to rocket exhaust.

The evidence for these compounds should be checked in other samples and, in view of the small concentrations reported, particularly great care should be taken in regard to contaminations. Likely, many compounds apparently are produced when chemical solutions are applied to the soils which contain highly activated carbon and other atoms from the solar wind. It has been shown particularly that CD_4 is produced when D_2O is used instead of H_2O [1]. Water is present in such low concentrations that it is very difficult to distinguish between indigenous water and terrestrial contaminations.

AGES

Two types of calculation have been considered in studying the age of lunar materials. Assuming that lunar materials were derived from meteoritic-type materials, we ask for the time since the materials of the lunar surface were separated from such meteoritic material, which is known as the "model age." It is assumed in calculating the $Rb^{87}-Sr^{87}$ age or the uranium-lead and thorium-lead ages that the ratios of concentrations of rubidium to strontium or of uranium and thorium to lead have not changed since the separation process.

The second type age measures the time since the sample was last melted or since the isotopes of the elements were last uniformly distributed between the minerals of the sample in question, the latter age known as the "isochron age."[3] The $Rb^{87}-Sr^{87}$ model age in the case of many lunar samples is about 4.6 aeons (10^9 years), this being the time required for the Sr^{87} in bulk samples to have evolved from the primitive strontium of 4.6 aeons ago as determined from the basaltic achondritic meteorites commonly referred to as BABI [51]. Isochron ages vary from 3.3 to 4.1 aeons. This means that the overall composition with regard to rubidium and strontium was acquired 4.6 aeons ago and was not changed in the reheating processes at later isochron dates. Ash flows at these later dates did not separate the liquid melt from a solid residue. This was probably due to the low gravitational field of the Moon where pockets of partially melted masses did not separate into liquid and solid layers, or it was due to complete melting of basaltic pockets so that no fractionation occurred.

The $K^{40}-Ar^{40}$ ages agree generally with the $Rb^{87}-Sr^{87}$ isochron ages, since argon would escape in the latest heating process. The U, Th–Pb ages of rocks are more complicated and do not agree with the $Rb^{87}-Sr^{87}$ ages, apparently due to loss of lead to the surroundings, probably by volatilization. An isochron plot for bulk soils and many rocks gives ages of 4.3–4.6 AE [52]. Since the soils and rocks have varying compositions, the volcanic flows occurred from isolated pockets which did not mix from the time of 4.6 AE until the flows occurred, i.e., 3.3 to 4.0 AE ago. Whether igneous activity occurred prior to 4.0 AE or after 3.3 AE is unknown.

An alternative suggestion is that the basaltic components were made by the usual terrestrial type of flow in which the basaltic liquid is separated from a solid fraction which remains at depth, and that uranium, thorium-lead, rubidium, and strontium were added later in varying amounts to the soil from some source materials which were produced 4.6 AE ago. In this case, it must be assumed that these initial basaltic rocks with low concentrations of these elements were produced by melting processes which regularly, in terrestrial cases, do produce basalts containing these elements. This seems most improbable, and it seems likely that the closed system melting explains these data and results from the low gravitational field.[4]

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[3] If an isotope with concentration x disintegrates to another isotope with present concentration y, and the concentrations t years ago were x_0 and y_0, all relative to a stable isotope of concentration r, then

$$\frac{y}{r}-\frac{y_0}{r}=\frac{x}{r}\left(e^{\lambda t}-1\right) \tag{2}$$

where t is the age and λ is the disintegration constant. This is the fundamental dating equation. If y/r and x/r are measured and y_0/r is assumed to be known from measurements on meteorites, the time t can be calculated. This is the model age. If y_0/r is unknown, but different crystals in the sample have varying values of y/r and x/r, these can be plotted on a graph, and the slope of the straight line is $(e^{\lambda t}-1)$ and the intercept on the y/r axis is y_0/r. The age can be calculated from the slope, and this is the isochron age [53].

[4] This is a brief summary of results obtained by several laboratories headed by G. J. Wasserburg, M. Tatsumoto, L. T. Silver, and W. Compston. (See refs. [3, 13, 14, 52, 56, 65, 68, 69, 70, 92].)

Two ages which are particularly interesting depend on the K^{40}–Ar^{40} ages as developed by Turner [77, 78, 79, 80], also on these and Rb^{87}–Sr^{87} ages reported by Schaeffer et al [61]. The "genesis rock" 15415 and anorthositic rocks of Apollo 16 have ages of about 4.1 AE. It was thought that some anorthositic rock ages might be 4.6 AE on the basis of the most primitive melting period occurring at that time, and that the anorthositic rocks were produced then. What reset the K^{40}–Ar^{40} clocks? Was it a hot Sun, an intense collisional process due to a collision catastrophe in the asteroidal belt, both of these, or something else?

LUNAR HISTORY

The highland areas of the Moon are known at present to consist of an anorthositic-type rock, and that this material and the titaniferous basalt acquired their composition through a melting process 4.6 ± 0.1 aeons ago. Later melting produced the rocks of Mare Tranquillitatis and Oceanus Procellarum. Mascons were produced during this interval and were supported by very rigid rocks from the time of formation until the present. The maximum subsurface temperatures consistent with support of the mascons are not known, but the subsurface temperatures of the Earth appear to be too high. Exact comparison is difficult because of the higher gravitational field of the Earth and its higher pressures in the outer layers. If the evidence for melting could be ignored, a low temperature history can be favored. If the mascons could be ignored, a high temperature history is immediately favored, i.e., if the evidence for the moments of inertia is ignored or explained. If all evidence is considered, a complicated history seems inevitable. In any case, the magnetic rocks are puzzling.

If the Moon was originally completely melted, it must have solidified and fractionated 4.5–4.7 aeons ago. The anorthositic layer solidified and floated at the surface, the pyroxene-olivine layer settled to the interior, and the titaniferous basaltic layer was between, or remained mixed with, other layers to be separated by subsequent closed system melting. The outer parts must have become cold enough to support the negative gravitational anomalies in Ptolemaeus and Albategnius and presumably in such craters over the entire surface. This occurred when the concentrations of radioactive elements were at maximum values [15, 16].

Many studies of lunar thermal histories have been made, which show how difficult it is to cool down a melted Moon in an aeon, even in the absence of radioactive elements. Possibly convection, as Tozer [72] points out, would be more effective. This has not happened to the Earth in 4.6 aeons, and positive gravitational anomalies are still not supported except through great convection cells. As long as lava flows occurred, the interior of the Moon would remain at high temperatures, and only an outer layer of rigid rocks would be possible, as with the Earth. It seems improbable, if not impossible, to explain the observations in this way. Without the evidence of the mascons, this postulated history would probably be more consistent with more lava flows than have been present, and particularly such a very high temperature history should have produced more general melting over the entire surface. The absence of great mare-type areas in the large craters of the far side suggests that the melting processes were just marginally possible.

If the moments of inertia indicated by orbiter and astronomical data are correct, an extensive layer of low-density anorthositic material, a small iron core, and high-density silicates on the interior are impossible without the addition of some high-density layer near the surface. It appears to be impossible that such a high-density layer was formed and supported, if the Moon was completely melted early in its history. But possibly the moment of inertia data are in error!

The suggestion has been made that the initial melting 4.5–4.7 aeons ago was limited to an outer layer of an initially cool Moon, and that the mascons were supported by the cool interior, and the negative anomalies of Ptolemaeus and Albategnius and other craters by an outer layer which had cooled rather rapidly. The sources of heating in this model are presumed to be:

(1) surface heating in a large gas sphere or during accumulation in such a sphere [6],
(2) surface heating by tidal effects during capture of the Moon,

(3) magnetic fields sweeping over the lunar surface and thus generating electric currents in silicate material preheated by some previously acting mechanism,

(4) heating in an accumulation process where rapid accumulation of solid objects occurred in the terminal stages; in cooling, the separation into several layers occurred with the titaniferous basalt solidifying last somewhere beneath the surface. Method (4) would appear to provide a very stirred condition not favorable for separation of the different layers indicated by the chemical studies.

The basalt was later melted and expelled from deeper layers. Radioactive heating was possible because of the very low thermal conductivity of a highly thermal-insulating dust layer at the surface. The shallow maria, consisting of ash flows over a very irregular surface, must have deep layers as well as shallow layers, and the deep layers should warm up markedly during hundreds of millions to a billion years, even if initially they were at low temperatures, i.e., 0° C, which need not have been the case. This is the model favored by the present writer [89, 97].

Previous suggestions assumed that the collisional history of early craters, maria, and mascons were produced early in lunar history, but if it is supposed that a catastrophic collision occurred in the asteroidal belt some 4 aeons ago, producing many large and small objects, and that these fell on the Earth, Moon, and other planets during some hundreds of millions of years, another history for the lunar surface can be devised. No record of such collisions would be retained on Earth if this occurred prior to the time the oldest terrestrial rocks were formed.

It must be assumed that the mascons result from rebound of the lunar rocks, and that the gravitational anomalies are supported in spite of a most massive and vigorous movement of rocky materials, since collisions of this kind should be at high velocities. Hence, the masses of such high-velocity colliding objects must be too small to account for the gravity anomalies. With this assumption, there may be little difficulty in having a sufficiently cold lunar surface in order to support the gravitational anomalies of Ptolemaeus and Albategnius. But the problem of supporting the mascons remains, if it is assumed that the titaniferous basaltic rocks flowed out on the surface from melts beneath the surface, which would seem the appropriate hypothesis for this suggestion of early lunar history.

Partial remelting in the lunar interior some 3.1 to 4.0 aeons ago, which is favored by some, would almost certainly fractionate rubidium and strontium relative to each other, hence, the model ages of the titaniferous basalts would almost certainly not be near 4.5 aeons. This is a strong argument against the origin of these materials by partial melting in the lunar interior.

From this discussion, it is concluded that the Moon was formed at comparatively low temperatures, heated on its surface by external heat sources, cooled sufficiently and at adequate depth to permit large craters, 150 km in diameter, to retain negative gravitational anomalies, and was able to support mass concentrations on the rigid interior. The differentiation of anorthosite, titaniferous basalt, and other fractions occurred during the cooling process. The soil resulted mostly from an ash flow and was remelted in limited amounts by radioactive heat due to the low thermal conductivity of the soil. This suggested history is complicated and will most probably be revised as more evidence is obtained.

The seismologists, Toksöz et al [71], secured evidence for an anorthositic layer extending to some 60 km below the surface and an interior below this of dunitic-type rocks rich in pyroxene and olivine. (This was discussed previously.) Very mild moonquakes (compared to earthquakes) occur, some of which originate repeatedly at points beneath the surface at depths of about 700–800 km. There are also reflections from structures at about the same depth which cannot be due to a metal core, but may be due to the boundary of some other type of central structure. This evidence favors the proposition that there was very deep or complete melting early in lunar history, but the evidence is not conclusive. The observations have been made over a very limited area and in regions relatively near the areas of the great mascons and collisional maria.

THE MAGNETIZED ROCKS OF THE MOON

A dipole magnetic field has not been detected on the Moon, but magnetized rocks of ages 4 to 3.1 aeons have been located at the Apollo landing sites, hence, magnetic fields must have been present up to that time or to later times, and the rocks cooled below the Curie point in this magnetic field. Also, rather large areas of the Moon are magnetized. The origin of the magnetic field responsible for producing these magnetized rocks is a puzzle to all students of this subject, and this question has an important bearing on lunar origin.

After the magnetic field of the Earth and a possible field from the Sun are discarded, we turn to a possible lunar dipole field which must have disappeared later than 3.1 aeons ago. One proposal advanced particularly [57] has been an iron core smaller than that of the Earth which, therefore, must have rotated very rapidly in order to produce the required field. This seems unlikely, and no iron core has been detected in the seismic observations which, however, may not be conclusive. If such a circulating iron core was present in the early period before 3.1 aeons ago, it has been suggested that it froze and, hence, no field would exist today. Another suggestion was that the interior of the Moon accumulated at low temperatures and magnetizable particles, i.e., iron, accumulated in a primitive magnetic field of the Sun to form a permanent magnetic dipole field which would persist until radioactive heating raised the temperature above the Curie point. However, in this case, the surface regions must have melted in order to produce the highly differentiated surface regions and ash flows on the surface.

A popular view is that the Moon accumulated from solid objects, at first at low temperatures, because of the low gravitational energy and rate of accumulation, and later at high gravitational energy and velocity of accumulation, thus producing a cold interior and a melted surface. It is estimated that the accumulation must have occurred in about 2000 years or less, in order to produce surface melting in spite of radiation loss. Also, this bombardment must have been terminated rather suddenly. It is difficult to specify a place in the solar nebula where this could occur. An alternative method is provided by the gas spheres [88]. In this case, the solids settle to the interior of the sphere when it is cold, but as the sphere contracts, the temperature of the sphere's interior rises, thus, the interior could form cold and the surface could accumulate at higher temperatures [6]. The Moon cooled after the high-temperature Sun blew the gas sphere away and, whichever way the Moon accumulated, the magnetic field carried by the cold interior magnetized the cooling surface rocks and disappeared when radioactive heating raised the temperature of the cold interior above the Curie point. It has been mentioned that this is a most interesting problem and one that has surprised many who study the Moon. (See reviews [58, 66].)

ORIGINS OF THE MOON

A discussion of the origin of the Moon requires considering the origin of the planets and their satellites—in fact, the origin of the solar system. Jupiter and its inner moons have the general orbital structure of the Sun and its planets, and the axis of Jupiter's rotation is nearly perpendicular to the plane of the ecliptic. If the other planets and their satellites resembled this planet in general structure, there would be no great disagreement in regard to questions of origin. It would be supposed that the planets and their satellites accumulated from smaller objects both solid and gaseous. However, the Earth, Venus, Mars, and major planets other than Jupiter have axes of rotation not perpendicular to the ecliptic, and this probably requires collisions of very massive objects to form the planets. This alone indicates the presence of such objects early in the solar system history.

If all the terrestrial planets had large moons similar to that of the Earth, it would be supposed that these planets and satellites formed as double planets, i.e., accumulation from solid or liquid silicate compounds in the immediate neighborhood of each other. Again, the problem of the Moon's origin would not have been discussed for many decades in this case. It is the uniqueness of the Moon as a single, very large satellite that poses the interesting and controversial question of its origin. But if the double planet origin is the rule, the absence of a large moon of Venus and some fairly large moons of Mercury and Mars becomes the disturbing question.

Cameron [9] and Ringwood [54] favored the view that the Earth and Moon accumulated quickly in some 10^3 or 10^4 years at very high temperatures and as a double body. The Moon accumulated from a volatilized mass of high-temperature material moving in a ring about planet Earth. The mass of the Earth, plus its proportion of solar gases, would be approximately equal to that of Jupiter originally dispersed over a disk surrounding the Sun. At some time, it is necessary that the 0.3% of the terrestrial-type material destined to form solid bodies separate from the 99.7% of gases and accumulate into a limited volume. This, seemingly, could only occur if these materials were at a sufficiently low temperature to condense to liquids or solids. Possibly, if solids settled to the median plane of the nebula, this would be possible. The model resembles, and in a way is identical with, protoplanets of Kuiper [30], which have the obvious difficulty of losing a mass of gas equal to that of Jupiter. Urey [81] argued that this is impossible and, up to the present, no satisfactory method of removing gases has been proposed. It may be, but is not certain, that the magnetic fields of the rotating magnetic dipole Sun may have provided such a mechanism. Soviet authors, especially Schmidt, Safronov, and Levin [36, 60, 62] are inclined to favor a theory suggesting the accumulation of a multitude of small satellites which surrounded the Earth during its synthesis and growth over 100 million years.

Ringwood [54] argues that the loss of volatiles so evident in lunar surface material shows that the Moon must have separated from high-temperature gases.[5] This is a very good argument especially if these elements have been depleted in the entire Moon—an untested assumption at present. The abundance of the more abundant elements in lunar materials are so similar to those expected from the fractionation of silicate materials by melting that it would appear that extreme volatilization methods are not required. Moreover, mechanisms for tilting the axis of the Earth and moving the Moon's orbit in some way are required, since Goldreich [21] showed that the present orbit of the Moon could not have originated in the plane of the Earth's orbit. Both these effects require the presence of other sizeable bodies which collided with the Earth and Moon to produce these effects. If they existed, similar objects colliding with other planets would produce similar effects.

That Venus does not have a moon and rotates in the reverse sense is probably the most damaging evidence in regard to this theory for Earth and lunar origin. Marcus [40] and Safronov [59] pointed out that such collisions were necessary, and Urey [82, 83] suggested methods of producing such objects. It has recently been proposed that large preplanetary objects existed and collided to form the Earth at high temperatures, and a Moon volatilized from the Earth, according to Ringwood's model. Elements volatile at 1500° K and lower are missing from the lunar surface, but there appears to be no reason to assume any important fractionation between silicon on the one hand and aluminum, magnesium, and calcium on the other, even though great differences in volatilities exist. This writer doubts the correctness of Ringwood's gaseous silica, alumina [etc] atmosphere as an origin for the Moon.

Possibly, if samples of rocks from the deeper layers of the Moon could be secured and showed low abundances of the very volatile elements, this would indicate that the materials of the Moon had been heated to some 1000–1500° C in fairly finely divided form, and that the volatiles were swept away with the residual gases. Those who believe that the titaniferous basalts are indeed lava flows from the interior will now accept this point as proven. This writer would like to see samples from what appear to be limited lava flows in various locations on the Moon and which might come from great depths, before accepting this conclusion.

Sir George Darwin suggested that the Moon escaped from the Earth, which has been discussed pro and con during this century. This

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[5] Ringwood has recently withdrawn his sponsorship of these suggestions.

discussion has been reviewed [49, 94]. The density of the Moon approximates that of the Earth's mantle, and this troublesome problem is solved immediately by this hypothesis. Much effort has been expended in showing that such a separation would be possible. Recently, this hypothesis has not been favored partly, and possibly decisively, by studies on the chemical composition of the lunar surface. The lunar basalts have definitely higher concentrations of iron and titanium and definitely lower concentrations of the more volatile elements than the Earth. It is certainly not impossible that these differences in a complicated high-temperature separation process could be produced, but it does appear improbable. The ages of lunar rocks would restrict the time of separation to before 4.5 aeons. One thing evident from the older data is important! If Venus and Earth evolved by similar processes at comparable distances from the Sun, why does the Earth-Moon system have a very large positive angular momentum relative to the orbital angular momentum, and Venus a small and negative value for this quantity? Why did not Venus also accumulate with a large axial rotation and separate into a double planet? These questions could have been asked many years ago. Today, separation of the Moon from the Earth is not favored and seems very unlikely.

The capture hypothesis has been especially popular since Gerstenkorn [18, 19] investigated this problem, and it has been discussed by others [4, 38]. This mechanism has the obvious advantage that it is an incidental origin, and it is not necessary to explain the absence of satellites of the other terrestrial planets. However, it must be assumed that many moons were present at some time in the early period of the solar system unless multiple, highly improbable assumptions are made. There is small probability of capture of the Moon in any orbit about the Earth rather than capture by impact on the Earth. These problems have been discussed in detail by Urey and MacDonald [88]. Gerstenkorn [19] concludes that capture occurred in a reverse orbit which turned over the Earth's poles and became direct. It was proposed that the minimum orbit was near the Roche limit of 2.9 Earth radii for an object of lunar density.

In this capture process, a great deal of energy must be dissipated as heat, i.e., some 10^{11} ergs per gram of the Moon. Part of this would be dissipated in the Moon, probably in the outer layers, and may have contributed to the production of its melted surface layer (discussed above). Such a melting process would be more concentrated in the hemisphere near the Earth and may aid in accounting for the more extensive maria areas in the nearer hemisphere. If such heating became general, the support of the mascons would be jeopardized. Urey and MacDonald [88] suggest that collisions with other objects moving about the Earth may have aided in the capture process, and that the initial orbit may have been much larger, thus avoiding the heating difficulty. Also, their proposal permits the angular momentum density of the initially accumulated Earth to lie on the empirical curve of MacDonald [38], who shows that the logarithm of the angular momentum densities of the planets plotted against the logarithms of the masses is a straight line of slope of about 0.82.

This model for lunar origin requires the premise that the Moon accumulated elsewhere. The method of accumulation and general chemical composition present problems for which solutions must be offered if the capture process is to be accepted. Until the present, only the gas sphere model of Urey [41, 82, 84] has been proposed, but others are possible, although difficult to calculate realistically. It is supposed that two dimensional gravitational instabilities occurred in a flat disk nebula following formulas first developed by Jeans and revised by Chandrasekhar [11]. The formulas are approximate when applied in this way, since the presence of solids probably increases the instability. Calculated temperatures in the nebula required to make lunar-sized objects are very low, and the calculated mass of the nebula is a substantial fraction of a solar mass. Some substantial loss of mass of this kind must have occurred in order to decrease the angular momentum of the primitive Sun as usually assumed by the Alfvén magnetic field mechanism, and Herbig [23] requires dust clouds of approximate solar mass in T Tauri stars.

Accumulation of lunar masses at the center of such gaseous objects due to gravitation with the energy of accumulation being absorbed by the great mass of gas could occur at low temperatures while the radii are large. If the gas mass contracted to smaller radii subsequently, the surface regions of the central lunar object could be heated to high temperatures, and reduced liquid iron would remove the siderophiles, and liquid iron sulfide would remove the chalcophiles (see [6]). With slow removal of the gas spheres, there would be slow cooling of the central mass, and, with complete removal of the gases, more rapid cooling to low temperatures. The composition remains a serious problem. With a low abundance of iron in the Sun relative to other elements (which has been fashionable for many years), the Moon consisted of primitive, nonvolatile solar matter, but with revised solar abundances, the density of primitive, solar nonvolatile matter becomes close to 4 g/cm^3 and does not agree with the lunar density.

If capture theory is to be seriously considered, explanation of this problem must be made. Carbonaceous chondrites are fairly abundant as observed falls, and the Type III Vigarano-type group have proper densities and a low abundance of potassium, so that a rigid interior of the Moon could be maintained if the central body had composition of this kind or similar. However, these meteorites contain water and considerable carbon. The low abundances of both these substances in the lunar surface are very unfavorable, but not fatal to this suggestion for the lunar interior.

Other methods [22, 39, 40, 59] have been discussed for accumulated sizeable objects from smaller solid objects without the presence of gases, which will certainly be necessary if the more volatile elements are missing from the interior of the Moon. In this case, successive events must provide for loss of volatiles at some 1500° K, and these must be driven out of the neighborhood where the Moon and Earth will accumulate before that accumulation takes place. If the volatiles are present in the deep interior of the Moon, then the accumulation of the Moon in a gas sphere is indicated, and the Earth accumulated from fragments of such objects.

Cameron [10] suggests that the Moon condensed from the gaseous solar nebula inside the orbit of Mercury where the least volatile elements, CaO and Al_2O_3, condensed. These accumulated into the Moon which was thrown by Mercury into an orbit crossing the orbits of Venus and the Earth, and was then captured by the Earth. Thus, the Moon was condensed in a region of the solar nebula where iron remained in the gaseous form to a considerable extent, and in this way, the low lunar density and possibly the chemical composition are accounted for. Both these mechanical events appear to be highly improbable, although not impossible.

If the Moon was captured, it was formed independently from the Earth and as a separate primitive planet. The present ages indicate that the Moon was present as a body at about the time the meteorites were formed, and all possibility of dating the Earth in the same way has been lost.

Jupiter and its satellites appear to be a small solar system (as stated previously) and a strong prejudice favors the formation of these satellites in the neighborhood of their primary. The seven moons of approximately lunar size in the solar system, and all other satellites and the asteroids having a combined mass of about 0.25 of one lunar mass, suggest that lunar-sized objects were favored in the solar system. The tilts of axes of the planets hint that some large objects were about and collided with the accumulating planets during the terminal stages of accumulation. Possibly our Moon is not such a unique object as it is often thought to be!

REFERENCES

1. ABELL, P. I., P. H. CADOGAN, G. EGLINTON, J. R. MAXWELL, and C. T. PILLINGER. Survey of lunar carbon compound. I. The presence of indigenous gases and hydrolyzable carbon compounds in Apollo 11 and Apollo 12 samples. *In, Proceedings, Second Lunar Science Conference*, Houston, Jan. 1971, Vol. 2, pp. 1843–1863. Cambridge, Mass., MIT Press, 1971.
2. ADLER, I., J. TROMBKA, J. GERARD, P. LOWMAN, R. SCHMADEBECK, H. BLODGET, E. ELLER, L. YIN, R. LAMOTHE, P. GORENSTEIN, and P. BJORKHOLM. Apollo 15 geochemical x-ray fluorescence experiment: preliminary report. *Science* 175:436–440, 1972.

3. Albee, A. L., D. S. Burnett, A. A. Chodos, O. M. Eugster, J. C. Huneke, D. A. Papanastassiou, F. A. Podosek, G. P. Russ II, H. G. Sanz, F. Tera, and G. J. Wasserburg. Ages, irradiation history, and chemical composition of lunar rocks from the Sea of Tranquility. *Science* 167:463–466, 1970.
4. Alfven, H. The early history of the Moon and the Earth. *Icarus* 1(4):357–363, 1963.
5. Arnold, J. R., J. I. Trombka, L. E. Peterson, R. C. Reedy, and A. E. Metzger. Lunar orbital gamma-ray measurements from Apollo 15 and Apollo 16. *In, Space Research XIII, Proceedings, 15th Plenary Meeting,* Madrid, May 1972, Vol. 2, pp. 927–933. Berlin, Akademie, 1973.
6. Bainbridge, J. Gas imperfections and physical conditions in gaseous spheres of lunar mass. *Astrophys. J.* 136(1):202–210, 1962.
7. Baldwin, R. B. Lunar mascons: another interpretation. *Science* 162:1407–1408, 1968.
8. Booker, J. R. Thermal state of the Moon. *Trans. Am. Geophys. Union* 51(11):774, 1970.
9. Cameron, A. G. W. The pre-Hayashi phase of stellar evolution. *In,* Kumar, S. S., Ed. *Low Luminosity Stars,* pp. 423–431. New York, Gordon and Breach, 1969.
10. Cameron, A. G. W. Properties of the solar nebula and the origin of the Moon. *The Moon* 7:377–383, 1973.
11. Chandrasekhar, S. The gravitational instability of an infinite homogeneous medium when a coriolis acceleration is acting. *In,* Beer, A., Ed. *Vistas in Astronomy,* Vol. 1, pp. 344–347, 1955.
12. Chandrasekhar, S. *Hydrodynamic and Hydromagnetic Stability.* New York, Oxford Univ. Press, 1961.
13. Compston, W., H. Berry, M. J. Vernon, B. W. Chappell, and M. J. Kaye. Rubidium-strontium chronology and chemistry of lunar material from the Ocean of Storms. *In, Proceedings, Second Lunar Science Conference,* Houston, Jan. 1971, Vol. 2, pp. 1471–1485. Cambridge, Mass., MIT Press, 1971.
14. Compston, W., B. W. Chappell, P. A. Arriens, and M. J. Vernon. The chemistry and age of Apollo 11 lunar material. *In,* Levinson, A. A., Ed. *Proceedings, Apollo 11 Lunar Science Conference,* Vol. 2, pp. 1007–1027. New York, Pergamon, 1970.
15. Crozaz, G. Evidence for extinct Pu^{244}: implications of extinct Pu^{244} in lunar material. *In,* Watkins, C., Ed. *Abstracts of Third Lunar Science Conference,* Houston, Jan. 1972, p. 165. Houston, Lunar Sci. Inst., 1972. (No. 88)
16. Crozaz, G., R. Drozd, H. Graf, C. M. Hohenberg, M. Monnin, D. Ragan, C. Ralston, M. Seitz, J. Shirck, R. M. Walker, and J. Zimmerman. Evidence for extinct Pu^{244}: implications for the age of the Pre-imbrium crust. *In,* Watkins, C., Ed. *Abstracts of Third Lunar Science Conference,* Houston, Jan. 1972, p. 164. Houston, Lunar Sci. Inst., 1972. (No. 88)
17. Fox, S. W., K. Harada, P. E. Hare, G. Hinsch, and G. Mueller. Bio-organic compounds and glassy microparticles in lunar fines and other materials. *Science* 167:767–770, 1970.
18. Gerstenkorn, H. Über Gezeitenbreibung beim zweikörper Problem. *Z. Astrophys.* 36:245, 1955.
19. Gerstenkorn, H. The model of the so-called "weak" tidal friction and limits of its applicability. *In,* Runcorn, S. K., Ed. *Mantles of the Earth and Terrestrial Planets,* pp. 228–234. New York, Wiley (Interscience), 1967.
20. Gold, T., and S. Soter. Apollo 12 seismic signal: indication of a deep layer of powder. *Science* 169:1071–1075, 1970.
21. Goldreich, P. History of the lunar orbit. *Rev. Geophys.* 4(4):411–439, 1966.
22. Hartmann, W. K. Growth of plantesimals in nebulae surrounding young stars. *Mem.* [8°] *Soc. Roy. Sci. Liege, 5th Ser.* 19:13–26, 1970.
23. Herbig, G. H. Pre-main sequence stellar evolution: introductory remarks. *Mem.* [8°] *Soc. Roy. Sci. Liege, 5th Ser.* 19:13–26, 1970.
24. Hodgson, G. W., E. Peterson, K. A. Kvenvolden, E. Bunnenberg, B. Halpern, and C. Ponnamperuma. Search for porphyrines in lunar dust. *Science* 167:763–765, 1970.
25. Kaula, W. M. Moon: gravitational field. *In, McGraw-Hill Yearbook of Science and Technology,* pp. 222–224. New York, McGraw-Hill, 1969.
26. Kaula, W. M., G. Schubert, R. E. Lingenfelter, W. L. Sjogren, and W. R. Wollenhaupt. Lunar topography from Apollo 15 and 16 laser altimetry. *In, Proceedings, 4th Lunar Science Conference,* Houston, Tex., March 1973, pp. 2811–2819. New York, Pergamon, 1973.
27. Kopal, Z. *The Moon,* p. 88. Dordrecht, Holl., Reidel, 1969.
28. Kopal, Z. On the depth of the lunar regolith. *The Moon* 1:451, 1970.
29. Koziel, K. Differences in the Moon's moments of inertia. *Proc. Roy. Soc. London, Ser. A* 296:248–253, 1967.
30. Kuiper, G. P. On the origin of the lunar surface features. *In, Proceedings, National Academy of Science,* Vol. 40, pp. 1096–1112. Washington, D.C., Nat. Acad. Sci. 1954.
31. Latham, G., J. Dorman, F. Duennebier, M. Ewing, D. Lammlein, and Y. Nakamura. Moonquakes, meteroids, and the state of the lunar interior. *In, Proceedings, 4th Lunar Science Conference,* Houston, Tex., March 1973, pp. 2515–2527. New York, Pergamon, 1973.
32. Latham, G. V., M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksöz, R. Wiggins, J. Derr, and F. Duennebier. Passive seismic experiment. *Science* 167:455–457, 1970.
33. Latham, G. V., M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksöz, R. Wiggins, J. Derr, and F. Duennebier. Apollo 11 passive seismic experiment. *In,* Levinson, A. A., Ed. *Proceedings, Apollo 11 Lunar Science Conference,* Houston, Jan. 1970, Vol. 3, p. 2309. New York, Pergamon, 1970.
34. Latham, G. V., M. Ewing, F. Press, G. Sutton, J. Dorman, Y. Nakamura, N. Toksöz, R. Wiggins, and R. Kovach. Passive seismic experiment. *In,*

Apollo 12 Preliminary Scientific Report, pp. 39–53. Washington, D.C., NASA, 1970. (NASA SP–235)

35. Levin, B. J. Thermal effects on the figure of the Moon. *Proc. Roy. Soc. London, Ser. A* 296:266–269, 1967.
36. Levin, B. Yu. Origin of the Earth. *Izv. Akad. Nauk SSSR, Fiz. Zemli* (7):5–21, 1972.
37. Lorell, J., and W. Sjogren. Selenodesy experiment. *In, Space Program Summary*, Vol. 3, pp. 47–50. Pasadena, Calif., Jet Propul. Lab., 1968.
38. MacDonald, G. J. F. Origin of the Moon; dynamical considerations. *In*, Marsden, B. S., and A. G. W. Cameron, Eds. *The Earth-Moon System*, p. 170. New York, Plenum, 1966.
39. Marcus, A. H. Positive stable laws and the mass distribution of plantesimals. *Icarus* 4(3):267–272, 1965.
40. Marcus, A. H. Formation of the planets by accretion of plantesimals: some statistical problems. *Icarus* 7(3): 283–296, 1967.
41. Marti, K., G. W. Lugmair, and H. C. Urey. Solar wind gases, cosmic ray spallation products and the irradiation history of Apollo 11 samples. *In*, Levinson, A. A., Ed. *Proceedings, Apollo 11 Lunar Science Conference*, Vol. 2, pp. 1357–1367. New York, Pergamon, 1970.
42. Michael, W. H., Jr., and W. T. Blackshear. Recent results on the mass, gravitational field, and moments of inertia of the Moon. *The Moon* 3:388–402, 1972.
43. Michael, W. H., Jr., W. T. Blackshear, and J. P. Gapcynski. Results on the mass and the gravitational field of the Moon as determined from dynamics of lunar satellites. *In*, Morando, B., Ed. *Dynamics of Satellites, Proceedings, 12th COSPAR Plenary Meeting*, Prague, May 1969, pp. 42–56. Berlin, Springer, 1970.
44. Muller, P. M., and W. L. Sjogren. Mascons: lunar mass concentrations. *Science* 161:680–684, 1968.
45. Muller, P. M., and W. L. Sjogren. Lunar gravimetrics. *In*, Donahue, T. M., Ed. *Space Research X*, pp. 975–983. Amsterdam, North-Holland, 1970.
46. Muller, P. M., and W. L. Sjogren. Private communication. 1970.
47. Nagy, B., C. M. Drew, P. B. Hamilton, V. E. Modzeleski, M. E. Murphy, W. M. Scott, H. C. Urey, and M. Young. Organic compounds in lunar samples: pyrolysis products, hydrocarbons, amino acids. *Science* 167:770–773, 1970.
48. O'Keefe, J. A. Isostasy on the Moon. *Science* 162:1405–1406, 1968.
49. O'Keefe, J. A. Origin of the Moon. *J. Geophys. Res.* 74(10):2758–2767, 1969.
50. O'Keefe, J. A., and W. S. Cameron. Evidence from the Moon's surface features for the production of lunar granites. *Icarus* 1(3):271–285, 1962.
51. Papanastassiou, D. A., and G. J. Wasserburg. Initial strontium isotopic abundances and the resolution of small time differences in the formation of planetary objects. *Earth Planet. Sci. Lett.* 5:361–376, 1969.
52. Papanastassiou, D. A., and G. J. Wasserburg. Rb-Sr age of a Luna 16 basalt and the model age of lunar soils. *Earth Planet. Sci. Lett.* 13:368–374, 1972.
53. Reynolds, J. H. Determination of the age of the elements. *Phys. Rev. Lett.* 4:8, 1960.
54. Ringwood, A. E., and E. Essene. Petrogenesis of Apollo 11 basalts, internal constitution and origin of the Moon. *In*, Levinson, A. A., Ed. *Proceedings, Apollo 11 Lunar Science Conference*, Houston, Jan. 1970, Vol. 1, p. 769. New York, Pergamon, 1970.
55. Roberson, F. I., and W. M. Kaula. Apollo 15 laser altimeter. *In, Apollo 15 Preliminary Science Report*, pp. 25:48–50. Washington, D.C., NASA, 1972. (NASA SP–289)
56. Rosholt, J. N., and M. Tatsumoto. Isotopic composition of thorium and uranium in Apollo 12 samples. *In, Proceedings, Second Lunar Science Conference*, Houston, Jan. 1971, Vol. 2, pp. 1577–1584. Cambridge, Mass. MIT Press, 1971.
57. Runcorn, S. K. Convection in the Moon and the existence of a lunar core. *Proc. Roy. Soc. London, Ser. A* 296: 270–284, 1967
58. Runcorn, S. K., and H. C. Urey. A new theory of lunar magnetism. *Science* 180:636–638, 1973.
59. Safronov, V. S. Sizes of the largest bodies falling onto the planets during their formation. *Astron. Zh.* 42(6): 1270–1276, 1965. (Transl: *Sov. Astron. J.*) 9(3):987–991, 1966.
60. Safronov, V. S. *Evolyutsiya doplanetnogo Oblaka i Obrazovanie Zemli i Planet.* Moscow, Nauka, 1969. (Transl: *Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets.*) Washington, D.C., NASA, 1972. (NASA TT–F–677)
61. Schaeffer, O. A., L. Husain, J. Sutter, J. Funkhouser, T. Kirsten, and I. Kaneoka. The ages of lunar material from Fra Mauro and the Hadley Rille-Apennine front area. *In*, Watkins, C., Ed. *Abstracts of Third Lunar Science Conference*, Houston, Jan. 1972, p. 677. Houston, Lunar Sci. Inst., 1972.
62. Schmidt, O. Yu. *A Theory of Earth's Origin; Four Lectures*, 3d ed. Moscow, Akad. Nauk SSSR, 1957; Moscow, Foreign Lang. Pub. (transl.), 1958.
63. Seeger, C. R. A geological criterion applied to Lunar Orbiter V photographs. *Mod. Geol.* 1(3):203–210, 1970.
64. Shoemaker, E. M., M. H. Hait, G. A. Swann, D. L. Schleicher, D. H. Dahlem, G. G. Schaber, and R. L. Sutton. Lunar regolith at Tranquillity Base. *Science* 167:452–455, 1970.
65. Silver, L. T. Uranium-thorium-lead isotopes in some Tranquillity Base samples and their implications for lunar history. *In*, Levinson, A. A., Ed. *Apollo 11 Lunar Science Conference*, Houston, Jan. 1970, Vol. 2, pp. 1533–1574. New York, Pergamon, 1970.
66. Sonett, C. P., and S. K. Runcorn. Electromagnetic evidence concerning the lunar interior and its evolution. *The Moon* 8(9):308–334, 1973.
67. Stipe, J. G. Iron meteorites as mascons. *Science* 162: 1402–1403, 1968.
68. Tatsumoto, M., and J. N. Rosholt. Age of the Moon:

an isotopic study of uranium-thorium-lead systematics of lunar samples. *Science* 167:461–465, 1970.

69. Tatsumoto, M., R. J. Knight, and B. R. Doe. U-Th-Pb systematics of Apollo 12 lunar samples. *In, Proceedings, Second Lunar Conference*, Houston, Jan. 1971, Vol. 2, pp. 1521–1546. Cambridge, Mass., MIT Press, 1971.
70. Tera, F., and G. J. Wasserburg. Oxygen isotope composition of the Luna 16 soil. *Earth Planet. Sci. Lett.* 13:455, 1972.
71. Toksöz, M. N., F. Press, K. Anderson, A. Dainty, G. Latham, M. Ewing, J. Dorman, D. Lammlein, G. Sutton, F. Duennebier, and Y. Nakamura. Lunar crust: structure and composition. *Science* 176:1012–1016, 1972.
72. Tozer, D. C. The Moon's thermal state and an interpretation of the lunar electrical conductivity distribution. *The Moon* 5:90–105, 1972.
73. Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson. Chemical analysis of the Moon at the Surveyor V landing site. *Science* 158:635–637, 1967.
74. Turkevich, A. L., J. H. Patterson, and E. J. Franzgrote. Chemical analysis of the Moon at the Surveyor VI landing site: preliminary results. *Science* 160:1108–1110, 1968.
75. Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson. Chemical analysis of the Moon at the Surveyor VII landing site: preliminary results. *Science* 162:117–118, 1968.
76. Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson. Chemical composition of the lunar surface in Mare Tranquillitatis. *Science* 165:277–279, 1969.
77. Turner, G. 40/argon-39 dating of lunar rock samples. *In*, Levinson, A. A., Ed. *Proceedings, Apollo 11 Lunar Science Conference*, Vol. 2, pp. 1665–1684. New York, Pergamon, 1970.
78. Turner, G. Ar^{40}–Ar^{39} ages from the lunar maria. *Earth Planet Sci. Lett.* 11:169–191, 1971.
79. Turner, G. Ar^{40}–Ar^{39} age and cosmic ray irradiation history of the Apollo 15 anorthosite 15415. *Earth Planet. Sci. Lett.* 14:169–175, 1972.
80. Turner, G., J. C. Huneke, F. A. Podosek, and G. J. Wasserburg. Ar^{40}–Ar^{39} ages and cosmic ray exposure ages of Apollo 14 samples. *Earth Planet. Sci. Lett.* 12:19–35, 1971.
81. Urey, H. C. Some criticisms of "On the origin of the lunar surface features" by G. P. Kuiper. *Proc. Nat. Acad. Sci.* 41(7):423, 1955.
82. Urey, H. C. The early history of the solar system as indicated by the meteorites (Hugo Mueller Lecture). *Proc. Chem. Soc.* (London), pp. 67–78, 1958.
83. Urey, H. C. Chemical evidence relative to the origin of the solar system. *Mon. Nat. Roy. Astron. Soc.* 131(3): 199–223, 1966.
84. Urey, H. C. III. Origin of the Moon. *In*, Runcorn, S. K., Ed. *Mantles of the Earth and the Terrestrial Planets*, pp. 251–260. New York, Wiley (Interscience), 1967.
85. Urey, H. C. Mascons and the history of the Moon. *Science* 162:1408–1410, 1968.
86. Urey, H. C., and H. Craig. The composition of the stone meteorites and the origin of the meteorites. *Geochim. Cosmochim. Acta* 4(1/2):36, 1953.
87. Urey, H. C., W. M. Elsasser, and M. G. Rochester. Note on the internal structure of the Moon. *Astrophys. J.* 129(3):842–848, 1959.
88. Urey, H. C., and G. J. F. MacDonald. Origin and history of the Moon. *In*, Kopal, Z., Ed. *Physics and Astronomy of the Moon*, 2nd ed., Vol. 1, Chap. 6, pp. 213–289. New York, Academic, 1971.
89. Urey, H. C., K. Marti, J. W. Hawkins, and M. K. Liu. Model history of the lunar surface. *In, Proceedings, Second Lunar Science Conference*, Houston, Jan. 1971, Vol. 2, pp. 987–998. Cambridge, Mass., MIT Press, 1971.
90. Van Dorn, W. G. Lunar maria: structure and evolution. *Science* 165:693–695, 1969.
91. Wänke, H. Chemistry of the Moon. *Top. Curr. Chem.* 44:115–154, 1974.
92. Wasserburg, G. J., G. Turner, F. Tera, F. A. Podosek, D. A. Papanastassiou, and J. C. Huenke. Comparison of Rb–Sr, K–Ar and U–Th–Pb ages: lunar chronology and evolution. *In*, Watkins, C., Ed. *Abstracts of Third Lunar Science Conference*, Houston, Jan. 1972, p. 788. Houston, Lunar Sci. Inst., 1972. (No. 88)
93. Wetherill, G. W. Lunar interior: constraint on basaltic composition. *Science* 160:1256–1257, 1968.
94. Wise, D. U. An origin of the Moon by rotational fission during formation of the Earth's core. *J. Geophys. Res.* 68(5):1547–1554, 1963.
95. Wise, D. U., and M. T. Yates. Mascons as structured relief on a lunar "Moho". *J. Geophys. Res.* 75(2):261–268, 1970.
96. Wood, J. A. Petrology of the lunar soil and geophysical implications. *J. Geophys. Res.* 75(33):6497–6513, 1970.
97. Wood, J. A. Thermal history and early magnetism in the Moon. *Icarus* 16(2):229–240, 1972.