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The interior of the Moon

As a result of the Apollo program we know that the lunar crust is much older than we had suspected, but the interior temperature remains a puzzle, as does the problem of the Moon's origin

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Full Moon from Apollo 17, showing (on right) part of the farside. Figure 1

The Moon is one of the more obvious of our neighbors in space and is certainly the most accessible. In spite of intensive analysis and probing by virtually every conceivable chemical and physical technique, the maneuvering room for speculation on lunar origin has scarcely diminished as a result of the Apollo program. This is not primarily due to lack of information but to the unexpected and confusing nature of the newly acquired data, most of which is open to multiple interpretations.

The Moon's unique characteristics have become even more unique as a result of lunar exploration. This strange body, shown particularly well in the Apollo 17 photograph (figure 1), is like no other in the solar system that we know about, either presently orbiting the Sun or having fallen on the Earth. It is similar to no planet or meteorite. Curiously, it is most like some tiny white inclusions in a meteorite that fell spectacularly to Earth in Mexico during the midst of the lunar exploration program.

The most immediate scientific and public-interest aspects of the lunar exploration programs have been the photographs and the returned lunar samples. The orbital and surface photographs form the basis of detailed morphological, historical and structural geological studies of the lunar surface. The samples have been subjected to a battery of chemical, petrological and physical measurements that has resulted in volumes of primary data and thousands of pages of interpretation. Less publicized, and less tangible to the layman, is the wealth of data that has been returned and is still being returned by the scientific instruments that accompanied the astronauts around and to the Moon (see figure 2).

These scientific observatories, more sophisticated by far than any that are operating on Earth, have measured the shape of the Moon, its gravity field, the electromagnetic fields in its vicinity, heat flow through the surface, the seismic activity and velocities in the interior and the composition of the surface and the tenuous lunar atmosphere.

From these measurements we can draw conclusions about the composition, temperature and history of the Moon; some of these conclusions confirm what we had already guessed from Earth-based observations, but others are unexpected. For example, we already knew that the Moon was deficient in iron (in comparison with the proportions of iron in the Earth and in the other terrestrial planets), but from examination of surface samples we now know that it is deficient also in all elements and compounds more volatile than iron. We had guessed that the Moon must have a low-density crust, but the great age and thickness of this crust were quite unexpected. The temperature of the interior is still a puzzle, with new evidence confirming neither the hot-core nor the cold-core theories—though I believe the hot-interior model is the more likely. Likewise we can still not be certain precisely how the Moon was formed, but we can make a scenario that not only fits the evidence we have for the Moon but also has useful things to say about the formation of the inner planets.

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Bulk chemistry

It has long been known that the density of the Moon is considerably less than that of the other terrestrial planets, even when allowance is made for pressure. The terrestrial planets contain about 30% iron, which is consistent with the composition of stony meteorites and the nonvolatile components of the Sun. They therefore fit into any scheme that has them evolve from solar material. Because iron is the major dense element occurring in the Sun, and presumably in the preplanetary solar nebula, the Moon is clearly depleted in iron. Many theories of lunar origin have been based on this fact, and numerous attempts have been made to explain how iron can be separated from other elements and compounds. Density, magnetic properties and ductility have all been invoked to rationalize why iron should behave differently than silicates in early solar-system processes.

Once samples were returned from the Moon, however, it became clear that the Moon was not only deficient in iron but in a number of other elements as well. The common characteristics of these elements and their compounds is volatility. The returned samples showed that the Moon is depleted in compounds more volatile than iron and that, to a first approximation, the Moon could be considered a refractory body. Calcium, aluminum and titanium are the major elements involved in high-temperature condensation processes in the solar nebula; minor refractory elements include barium, strontium, uranium, thorium and the rare-earth elements. The Moon is enriched in all these elements and we are now sure that more than simply iron-silicate separation must be involved in lunar origin.

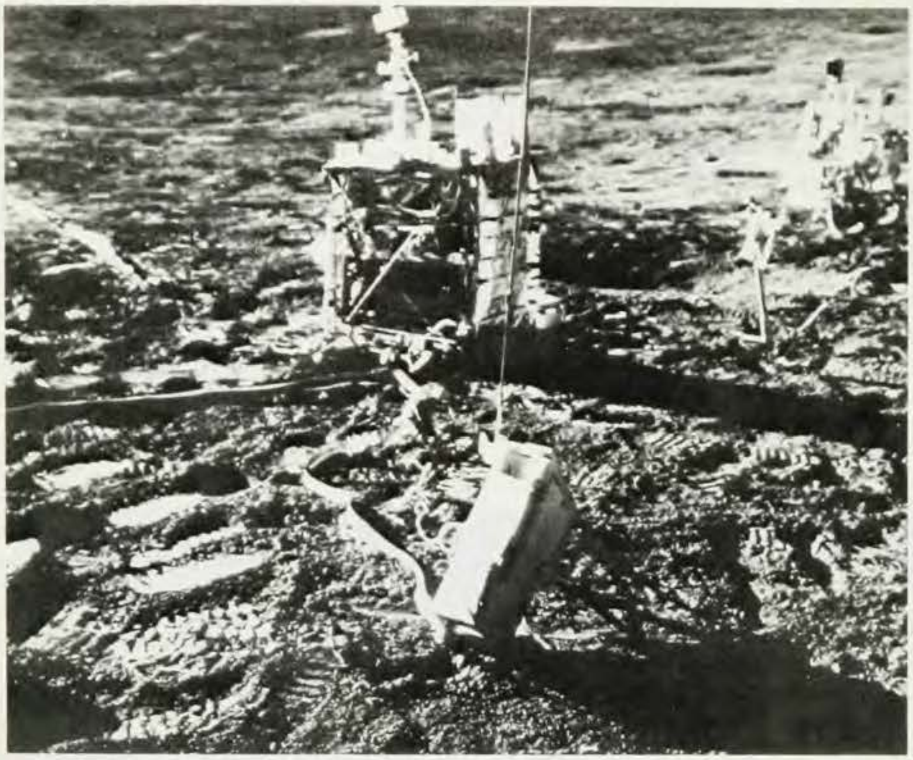
The abundance of titanium in the returned lunar samples was one of the first surprises of the Apollo program. Titanium is not exactly rare on Earth, but it is usually considered a "minor" or "trace" element. The first samples returned from the Moon contained 10% of titanium-rich compounds. The surface samples were also remarkably depleted in such volatile elements as sodium, potassium, rubidium and other elements that, from terrestrial and laboratory experience, we would expect to find concentrated in the crust. Water, sulfur and other volatile elements and compounds were also sparse. The refractory trace elements—such as barium, uranium and the rare-earth elements—were concentrated in lunar surface material to an extent several orders of magnitude over that expected on the basis of cosmic or terrestrial abundances.

Some of these elements, such as uranium, thorium, strontium and barium, are "large-ion" elements, and one would expect them to be concentrated in melts that would be intruded or extruded near the surface. However, other volatile large-ion elements, such as sodium and rubidium, are clearly deficient, in most cases by at least several orders of magnitude from that expected from cosmic abundances. The enrichment of refractory elements in the surface rocks is so pronounced that several geochemists proposed that refractory compounds were brought to the Moon's surface in great quantity in the later stages of accretion. The reason behind these suggestions was the belief that the Moon, overall, must resemble terrestrial, meteoritic or solar material and that it was unlikely that the whole Moon could be enriched in refractories. In these theories the volatile-rich materials must be concentrated toward the interior. In a cooling-nebula model of planetary formation, the refractories condense before the volatiles and it was therefore proposed that Moon was made inside out!

However, it now appears that the depletion of iron and volatiles can be taken at face value and that the whole Moon is deficient in elements and compounds more volatile than iron. Petrological considerations show that not only the surface rocks but also their igneous source regions, deep in the Moon, are also depleted in volatiles. The Moon is probably enriched in calcium, aluminum, titanium and the refractory trace elements throughout. This composition would explain the mean density of the Moon and the high heat flow, and it would help to explain why the Moon melted and differentiated very rapidly.

The interior

In view of the abundant geological evidence that the surface rocks resulted from melting processes in the interior, it was no surprise that the geophysical evidence indicated that the Moon has a low-density crust. Its great age, as measured by geochemical techniques, and great thickness, as re-



Scientific instruments taken to the Moon and left there by Apollo-14 astronauts are telemetering data back to Earth. (This photo and figure 1 from NASA.) Figure 2

quired by the physical evidence, were, however, unexpected. These are important boundary conditions on the origin and composition of the Moon.

The Moon's principal moments of inertia indicate that crustal thickness varies from about 40 km at the poles to more than 150 km on the lunar backside.[1] Large variations in crustal thickness are also required to satisfy gravity data and the noncoincidence of the centers of mass and figure of the Moon. The present orientation of the Moon and the restriction of basalt-filled maria to the Earth-facing hemisphere are undoubtedly the result of this asymmetry in crustal thickness.

The laser altimeter flown on some of the later Apollo missions provided details of topography as well as clarifying major problems such as frontside–backside asymmetry, offset of center-of-mass, elevation differences between maria and highlands and relative roughness of highlands compared to maria basins.[2] The maria are remarkably smooth and level; slopes of less than one tenth of a degree persist for hundreds of kilometers and topographic excursions from the mean are generally less than 150 meters. By contrast elevation differences in the highlands are commonly greater than 3 km. The mean altitude of the terrace, or highlands, above maria is also about 3 km.

The center of mass is displaced toward the Earth and slightly toward the east by about 2 km. This gross asymmetry of the Moon has long been known from consideration of the principal moments of inertia. The differences between the principal moments of inertia are more than an order of magnitude greater than can be accounted for by a simple homogeneous body, rotating and stretched by Earth tides. The simplest interpretation is in terms of a crust of highly variable thickness, an interpretation supported by nearside gravity results.

Asymmetry is not a unique characteristic of the Moon; the asymmetric distribution of continents and oceans on the Earth is well known, and Mars, likewise, is very asymmetric both in its topography and gravity field. Large-scale convection associated with early gravitational differentiation could lead to the observed asymmetries and may be one common characteristic of all the terrestrial planets.

In the case of the Earth and the Moon, and probably for Mars as well, the physical asymmetry correlates well with, and is probably the result of, chemical asymmetry. The lunar highlands are dominately plagioclase feldspar-rich rocks with densities considerably less than the frontside mare basalts and the mean density of the Moon. These feldspars crystallize at higher temperatures than basalt does and can therefore be expected to float to the surface of their parent liquid. The residual liquids would likely be the source region of the mare basalts, which erupt to the surface later.

This scenario not only explains the physical measurements but also some subtle details of the chemistry. Large-ion refractory elements are preferentially retained by the liquid, and therefore such elements as barium, strontium, uranium and thorium would be concentrated in the last liquid to crystallize. These elements are concentrated in the lunar-mare basalts by several orders of magnitude over the highland plagioclase-rich material, with the notable exception of europium, which is retained by plagioclase. Compared to the other rare-earth elements europium is depleted in basalts and enriched in anorthosites. The "europium anomoly" was one of the early mysteries of the lunar sample-return program and implied that plagioclase was abundant somewhere on the Moon. The predicted material was later found in the highlands.

Seismic evidence

Seismology is one of the most powerful tools for studying the interior of a planet, providing as it does information relevant to structure, composition and tectonics. In the case of the Earth, the major regions such as the crust, mantle and core and the sites of most earthquakes were discovered in the early days of seismology. At that time only a few seismic stations were in operation, and seismic waves were used not only to determine velocities but to determine the locations of the earthquakes as well. When earthquakes became better located, with networks of seismic stations, the structure of the Earth could be refined. As the velocity distribution in the Earth became better known the earthquake could be located with more certainty. Even today, with hundreds of seismic stations and thousands of well located earthquakes and large explosions, the refinement of Earth structure continues.

Currently four seismic stations are operating on the Moon, although two of them are so close together that the information they provide is partially redundant. For the problem of locating moonquakes this is a minimum network. In a homogeneous sphere four parameters are required to specify the location and time of occurrence of an unknown event. If the propagation velocity in the sphere is unknown more parameters are required. In general each seismic station, if appropriately placed, provides one parameter—usually the arrival time of the fastest phase, the direct compressional wave arrival. If the sphere is not homogeneous, additional parameters and seismic stations are required. For these reasons the locations, particularly the depths, of moonquakes must be considered tentative.

But it is clear that the seismic activity of the Moon is much less than the Earth, both in numbers of quakes and their size, or magnitude. Their times of occurrence appear to correlate with tidal stresses caused by the varying distance between the Moon and the Earth. Compared with the Earth they seem to occur at great depth, about half the lunar radius (but we must keep in mind the reservations on location accuracy mentioned above). Both the age-dating evidence and the seismic data indicate that the Moon today is a relatively inactive body. This conclusion is consistent with the absence of obvious tectonic activity and with the low level of stresses in the lunar interior implied by gravity and moment-of-inertia data.

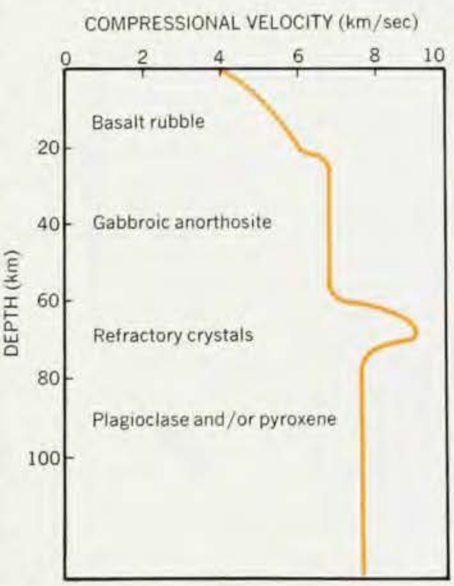
On the Earth, most, if not all, seismic and tectonic activity is associated with the movements of large plates on or near the Earth's surface. The driving mechanism of plates is only vaguely understood, but the extreme mobility of plates is probably related to their thinness relative to the radius of the Earth; the mass and thermal inertia of the lithosphere are negligible compared to the Earth as a whole. The ability of plates to break and slide past, or drive beneath, one another are consequences of their thinness. A variety of observations can be explained if the lunar lithosphere is much thicker than its terrestrial equivalent. Because the depth of the lithosphere is believed to be controlled by the intersection of the temperature-depth curve with the "solidus" (the temperature at which partial melting occurs), a thick lithosphere means either higher melting temperatures, or a shallow temperature gradient, or both. Both, in fact, are probable for the Moon. The Moon, being a smaller body than the Earth, will cool faster; the rarity of volatiles, including water, means that melting temperatures will be greater, and the refractory nature of the bulk of the lunar crust would drive melting temperatures even higher. The lunar heat-flow values are less than terrestrial ones, and this reduction is also consistent with a shallower temperature gradient.

The travel times of seismic waves generated by artificial impacts have been used to determine the structure of the outer 150 km of the Moon.[3] To produce useful impacts, Saturn IV-B booster and lunar-module ascent stages were programmed to strike the surface of the Moon at distances as far as 1750 km from the lunar seismic stations. The resulting velocity structure applies roughly to the central portion of the lunar frontside. We should keep in mind our previous discussion of inhomogeneity, particularly the rather strong evidence that crustal thickness varies substantially. Lateral changes in structure and velocity also complicate seismic interpretations.

The shallow crustal structure has been determined by the active seismic experiment,[4] which used thumper and mortar-launched grenade sources, and by surface gravity traverses. The outer kilometer has extremely low velocities, less than 1 km/sec. This value is more appropriate for rubble than consolidated rock. The velocities increase from 4 km/sec at 1 km depth to 6 km/sec at 20 km (see figure 3). The lower velocity is appropriate for consolidated rubble or extensively fractured igneous rock, such as basalt. The increase of velocity with depth is probably primarily the result of consolidation and crack closure. The 6-km/sec velocity at the base of this layer is consistent with laboratory measurements on returned samples of lunar basalt.

At 20 km depth the velocity increases abruptly to about 6.7 km/sec, and it remains relatively constant to 60 km depth. The constancy of velocity means that most cracks have been eliminated and also that the effects of temperatures and pressure gradients are either small or they cancel. In this region the velocities can be matched by anorthositic gabbro, a plagioclase-rich rock type that is low in iron and has relatively low density (about 2.9 gm/cm^3). This layer may be similar in composition to the lunar highlands.

At 60 km the velocity jumps, at least locally, to about 9 km/sec. When all the seismic data are considered together we may find that this layer is very thin (less than 40 km) or it occurs only locally, or both. Perhaps it occurs only as pods or lenses under maria basins or only under mascon basins; at the moment we have no way of telling. In any event, such high velocities were unexpected and are unusual by any standards. They may also be fictitious, because seismic waves refracted by dipping interfaces can give apparent velocities slower or faster than real velocities. A velocity of 9 km/sec is much greater than the 8 km/sec velocity typical of the Earth's upper mantle and of rocks thought to be common in the upper lunar mantle. Only a few minerals, exotic by terrestrial standards, have such high velocities. These include spinel ($MgAl_2O_4$), corundum (Al_2O_3), kyanite (Al_2SiO_5) and Ca-rich garnet ($Ca_3Al_2Si_3O_{12}$). These are all calcium- and/or aluminum-rich minerals and occur as the dense residual crystals when a Ca-Al-rich liquid partially solidifies. The 9-km/sec layer may therefore be related petrologically to the overlying crustal layer.



Compressional velocity plotted against depth in the Moon, with an indication of possible mineral assemblages present at different depths (From ref. 3.) Figure 3

The apparent seismic velocity at greater depth is only 7.7 km/sec—intermediate between the velocities we usually associate with the crust and the mantle. This velocity continues to a depth of at least 150 km (the deepest depth of penetration of seismic energy from artificial impacts) and is appropriate for pyroxene or plagioclase-rich rocks. In the latter case we would still be monitoring the crust and therefore would have only a lower bound, 150 km, on its thickness. It should be recalled that the crust is thicker on the backside. Even if the crust is only 60 km thick, the conventional interpretation of the seismic results, it is much thicker than the average terrestrial crust, particularly in relative terms; this great thickness indicates that the Moon was extensively differentiated. In combination with the age data this means that the Moon was extensively melted early in its history. The source of this early heat is a matter of some controversy.

Evidence for the constitution of the deeper interior is very sketchy. Seismic shear waves apparently cannot pass efficiently below some 1000 km depth. This can be taken as tentative evidence for at least a hot, if not molten or partially molten, deep interior.

Is the Moon hot or cold?

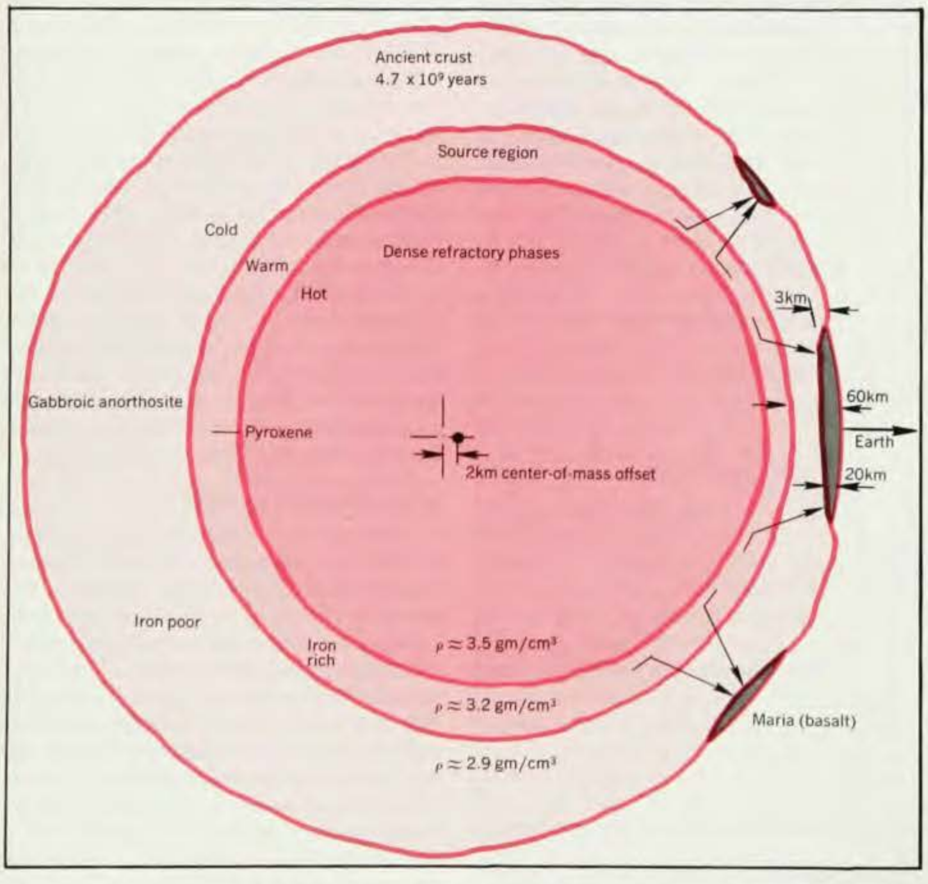
One of the long-standing controversies regarding the Moon is whether its interior is hot or cold. Most of the newer evidence is ambiguous and fails to resolve the controversy that originated with the earlier data. The widespread occurrence of basalt certainly indicates that it was at least partially molten early in its history, but we are not sure that this happened since then. Conduction alone is only efficient in lowering the internal temperatures of the outer 300 km; on the other hand the process of basalt extrusion is an efficient mechanism for removing heat. However, basalts are unlikely to have originated deeper than 500 km, and they represent only a small fraction of the Moon. Therefore they are ineffective in cooling the deep interior. The anorthositic highlands are probably also the result of igneous and differentiation processes. But their emplacement mechanism would be plagioclase flotation, resulting in a thick insulating blanket for the remaining liquid. The age of maria material indicates that melts still existed at moderate depths for more than 10^9 years after creation of the plagioclase-rich highlands.

It is quite possible that the mare-forming igneous episodes were a result of thermal, tidal and impact stresses, all of which were intense in the earliest history of the Moon. Igneous activity may have ceased when stresses were no longer adequate to breach the thick lithosphere. If this is true, then the Moon below some 300 to 1000 km may still be partially molten. A lithosphere of this thickness could easily support the stresses implied by the nonhydrostatic shape of the Moon and the presence of mascons.

The nonequilibrium shape of the Moon, the offset of the center of mass from the center of figure and the presence of large surface concentrations of mass (mascons) have been used as arguments that the Moon is a cold, strong body. However, when viewed more carefully, all of this evidence suggests just the contrary. The stresses required to support the nonequilibrium shape are only some tens of bars, and a relatively thin, strong, outer layer would suffice to support these stresses. The Earth, by contrast, supports stress differences of hundreds of bars, and stresses at kilobar levels are required to break rocks in the laboratory. Thus, taken at face value, the lunar data suggest that the Moon is a hot weak body. This conclusion is consistent with the lunar heat-flow values, the low level of seismic stresses and the high radioactivity inferred for the interior. Figure 4 shows the cross section of the Moon according to this picture.

If a small body such as the Moon formed hot it is likely that the other planets also formed hot, and that they too are differentiated. This is an important boundary condition on the vaguely understood processes of planetary formation. The accretion of planetesimals into planets must have been extremely rapid, at least in the time scale of cooling of the nebula. Otherwise the gravitational energy of accretion would be conducted to the surface and radiated away. A rapid time scale of accretion is consistent with modern theories of planetary accretion in a collapsing gas-dust cloud. High initial temperatures are also consistent with the hypothesis of accretion during condensation, which has been proposed to explain the differences in composition of the terrestrial planets. Briefly, this hypothesis states that the planets formed rapidly while the nebula was stijl cooling and that the nebula was dissipated before cooling or condensation was complete (see figure 5). The outer planets would be rich in volatile materials because of their distance from the Sun. Mercury would be the most refractory-rich terrestrial planet, insofar as distance from the Sun is the main variable. Its high density suggests that the nebula was dissipated shortly after iron condensed in its vicinity.

How can we explain the early high-temperature history of the Moon and at the same time its rapid death as an active body? Prior to lunar exploration the preferred theory for the formation of the planets involved the gradual accretion of cold particles with subsequent heating, melting and differentiation resulting from decay of radioactive elements. Because the first 10^9 years of terrestrial history are inaccessible to us there was no compelling reason to suppose that the Earth was initially hot. Some indirect clues, however, point to a high-temperature origin. The oldest terrestrial rocks are clearly the result of igneous processes, and they contain evidence that the Earth had a magnetic field when they crystallized. This suggests that the Earth had a molten core early in its history. Many ancient meteorites also have clearly gone through a high-temperature event or are the result of magmatic processes that predate the oldest traceable magmatic events on the Earth. These processes must have taken place in a body much smaller than the Earth.



Schematic cross section of the Moon, showing the variations in crustal thickness required to satisfy gravity data and the offset position of the center of mass. Figure 4

Age dating of lunar material indicates that most of the differentiation of the Moon occurred in the first 10^9 years of its existence. For the Earth most of this early record is lost because of subsequent igneous and volcanic activity and rapid erosional processes. The Moon, unlike the Earth, has been remarkably quiescent for the last 3×10^9 years. This is true not only for internal processes but also for the external bombardment processes that are mainly responsible for the surface features of the Moon. Both the internal structure and exterior morphology were apparently the result of an extensive early history of activity.

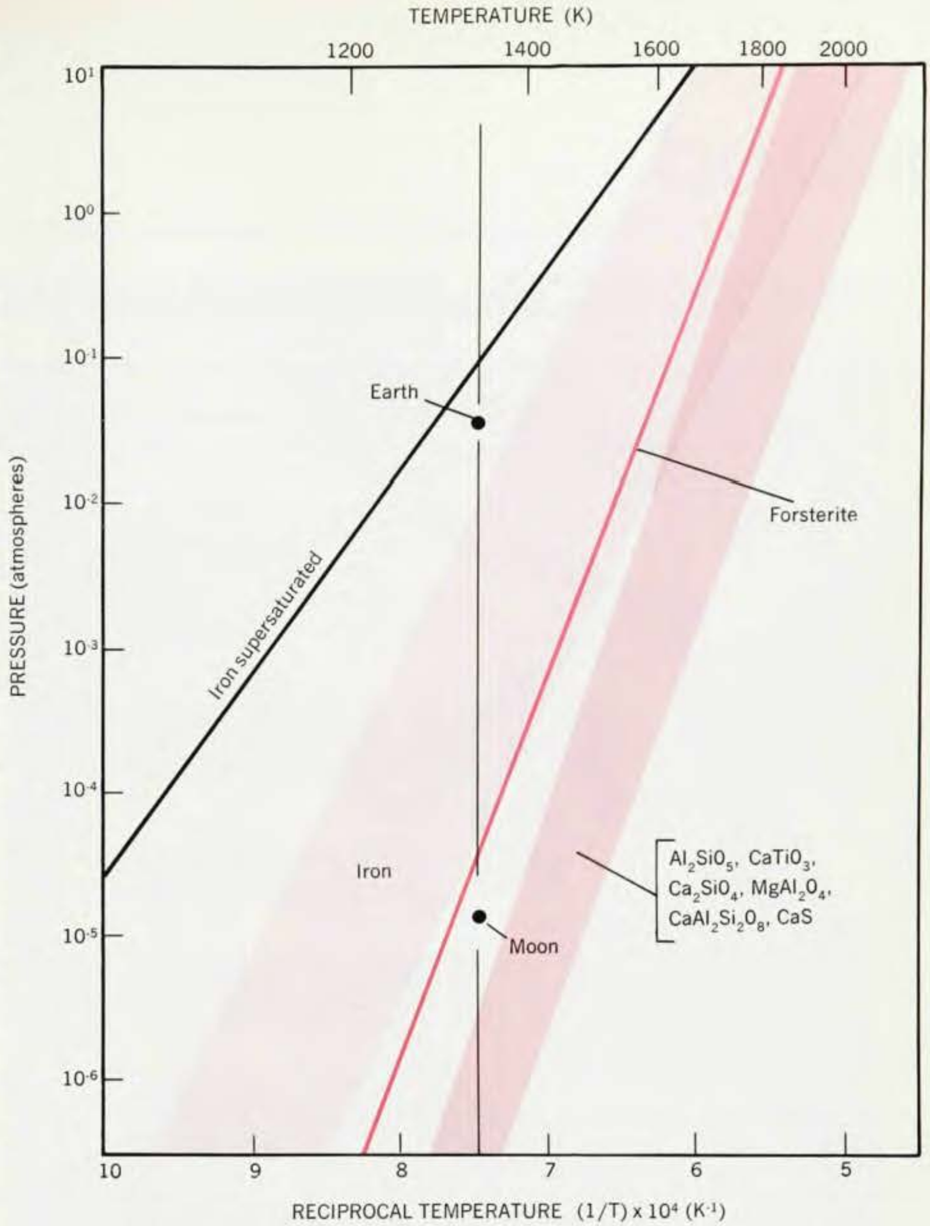
Many sources have been proposed as early heating processes. These include short-lived radioactive elements, solar radiation, high temperatures associated with the early nebula, and energy of gravitational accretion. For any of the latter three processes to be effective the bodies in the solar system must have assembled very quickly. Gravitational collapse of a gas-dust cloud is an attractive way both to localize protoplanetary material and to have initially high temperatures. The main problem is to be able to build planetary nuclei to a size big enough that they can effectively scavenge the remaining material in their vicinity.

The origin of the Moon

Some of the most obvious facts about the Moon may also be among the most relevant for our attempts to understand its origin. It is small, light and is close to a more massive body. These simple facts may all be related, for it is unlikely that preplanetary processes resulted in a single nucleus for each of the present planets. The nebula probably evolved from a disc to a series of rings; each ring in turn collapsed to a series of local gas-dust concentrations that collapsed further to form protoplanets, the building blocks of the planets.

Variations in the eccentricities and inclinations of the orbits of protoplanets at this stage of development ensure that they periodically approach each other; encounter velocities between bodies in a ring are low, and concentration rather than dispersal is the natural result. It is not difficult to believe, although certainly difficult to prove, that eventually one body will predominate; the remaining bodies will impact, orbit temporarily before impact, or orbit permanently. The scenario repeats for those bodies in orbit about the primary body. The largest nucleus, the Earth in this case, grows at the expense of the smaller particles and, if all this is happening in a cooling nebula, it will inherit most of the later, lower-temperature condensates.

In a cooling nebula of solar composition the first compounds to condense are calcium-, aluminum-, and titanium-rich oxides, silicates and titanates. These compounds comprise approximately 6% of the nonvolatile composition of the nebula, which is roughly everything but hydrogen, helium, carbon and that oxygen which is not tied up in the refractory compounds. Carbonaceous chondrites are usually taken as an approximation to the "nonvolatile" content of the nebula. Planetesimals formed at this point will be deficient in iron, magnesium, silicon, sulfur, sodium and potassium, all of which are still held in the gaseous phase. Solid particles will rapidly concentrate toward the median plane to accrete into refractory-rich planetary nuclei. While cooling of the nebula continues, iron and magnesium silicates condense; these are the most abundant constituents of meteorites and of the terrestrial planets. The largest body at any distance from the Sun will obtain the major share of these later condensates. In this scenario the Moon is one of the original smaller bodies that avoided impact with, or expulsion by, the Earth. It may also represent the coagulation of many smaller bodies that were trapped into Earth orbit from Earth-crossing solar orbits. In this hypothesis many of the satellites in the solar system may be more refractory than their primary bodies.



Condensation temperature versus pressure in a nebula of solar composition, to illustrate the hypothesis of planetary formation discussed in the text. (From ref. 5.) Figure 5

Type I and II carbonaceous chondrites contain about 10% of unique white inclusions, composed primarily of exotic Ca–Al-rich minerals such as gehlenite, spinel and anorthosite. These inclusions are rich in barium, strontium and uranium and the rare-earth elements, and they have most of the properties that have been inferred for the Moon. They are also very ancient. This material, together with the Moon, may represent the most primative material in the solar system and be the initial building blocks of the planets.

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