achieving the stable, fractionated, extended-chain crystalline form. The physical properties of the resulting polycrystalline structure are very strongly dependent upon the amount and kind of molecular folding which has occurred. In general, folded-chain crystals are tough and ductile and tend to produce low modulus and high elongation, whereas extended-chain crystals are brittle and tend to have higher modulus.

Calculations based upon the large anisotropy of bonding forces indicate that there may exist under some conditions (for example, in polyethylene at temperatures below 110°C) a true metastable equilibrium state which restricts the size of growing crystals. However, it is most likely that the folded-chain crystals result from strictly kinetic factors—that the observed fold-length is that fold-length which can grow fastest. Such folded-chain crystals are metastable in the sense that, below their growth temperature, their rate of change to a more stable form is negligibly slow. However, when heated to temperatures above the original crystallization temperature, they undergo annealing. This process consists of a refolding of the molecules into crystals with longer, and hence more stable, molecular fold-lengths. At the same time, the annealing process involves a rejection of somewhat longer low-molecular-weight molecules, which ultimately crystallize into stable, fractionated, extended-chain crystals. The increase in the ratio of extended-chain to folded-chain crystals, along with the greater fold-length, is consistent with the increase in density and modulus which accompanies annealing.

When a folded-chain crystal is deformed, at least some of the molecules are unfolded in some manner (as yet not understood) which results in retention of the molecules in a substantially crystalline array. The crystals of partially unfolded molecules which result from the deformation of folded-chain crystals are the major components of most oriented films and fibers. Our understanding of the physical properties of these materials rests upon our ability to determine the relative amounts and the distribution of extended-chain, folded-chain, and partially unfolded-chain crystals.

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Meteorites and the Moon

Cosmic-ray ages and contaminants provide evidence that meteorites may come from the moon.

Harold C. Urey

Some years ago I presented a paper before the National Academy of Sciences arguing that there was some evidence that stone meteorites came from the moon (*1*). I advanced two arguments, first, that the low cosmic-ray ages of stone meteorites were consistent with orbits moving in the earth's neighborhood, while the higher cosmic-ray ages of the irons were consistent with an asteroidal origin, and second, that the polymict character of many stones, both chondritic and achondritic, indicated that they had places of origin physically near each other, such as neighboring regions on the moon or other planetary bodies. During the years since then I have considered other features of the meteorites which might be consistent with a lunar origin. The differing composition of the chondritic meteorites and the nonvolatile fraction of the sun, particularly with respect to iron, indicates that these objects are mixtures of materials from various sources such as might have been produced by the great collisional processes on the moon. The origin of chondrules is a controversial subject, but collision processes may produce melted silicate objects of complicated structure, and it seems probable that chondrules will be found on the lunar surface or below the surface layer affected by micrometeorite bombardment. Finally, I argued (*2*) that if biological material is present in some of the carbonaceous chondrites, then this would be consistent with the approximate solar composition of the inorganic elements

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in these objects only if a primitive object had been contaminated by biological material which had evolved on some other object, and I suggested that the moon was the primitive object which became contaminated during its escape from or capture by the earth at a time when primitive organisms had evolved on the earth.

During recent years other evidence in regard to these problems has been developed. The Pribram meteorite fell in Czechoslovakia and its orbit was carefully observed. Its aphelion distance was 4.2 astronomical units; thus it appeared to be an asteroidal object, and yet its cosmic-ray age is 12×10^6 years (*3*), similar to the ages for other stone meteorites. This did not agree with the hypothesis of high cosmic-ray ages for asteroidal objects and low ages for objects moving near the earth's orbit. On the other hand, Arnold has shown (*4*) that objects originating from the moon with only small velocities beyond the escape velocity could acquire orbits of the Pribram type as a result of passes close to the earth and, in fact, that after some millions of years the objects that leave the moon and have not been captured would be expected to have orbits extending to great distances from the sun. But Arnold also finds that it is difficult to account for the low cosmic-ray ages of the stones as being due to collisions, and thus destruction, of stone meteorites in the asteroidal belt, because the number of objects required in the asteroidal belt to secure collisions in times of the order observed would be so large that much more light should be reflected from this region than is observed. Thus it is possible that the Pribram meteorite originated from the moon and was accelerated to a very elliptical orbit. It is also probable that collisions of comet heads with the moon would accelerate objects to fairly high velocities and thus the probable capture by the earth would be decreased. Again, the Farmington and Cold Bokkeveld meteorites have cosmic-ray ages below 10^5 years (*5*), and though these might come from the asteroidal belt by improbable processes, short lifetimes in space are more probable if the object originated near the earth. Zähringer (*6*) has pointed out that a definite grouping of cosmic-ray ages of the bronzite chondrites occurs at 4 million years and that an origin near the earth is a probable explanation for this fact. Some evidence for other groupings at somewhat greater ages exists. Anders's argument that a sufficient number of stone meteorites could not be removed from the moon by iron meteorites neglects the probable collisions of comet heads as a source of the stone meteorites. The head of the comet that fell in Siberia in 1908 probably had a mass about of 10^5 tons and probably would have removed much material from the moon had it fallen there. Fechtig *et al.* (*6a*) have secured accurate diffusion data and have shown that the inert gases could be retained at lunar subsurface temperatures for 4.5 eons. At present it seems reasonable to estimate that this evidence indicates an equal probability for lunar and asteroidal origins of stone meteorites.

The Ranger 7 pictures show that craters as large as 900 meters in diameter have been produced in Mare Cognitum by objects from Tycho 1000 km distant. Such objects must have had a minimum velocity of 1.12 km/sec and may have had a velocity as high as 1.68 km/sec if in a circumsurface orbit, and 2.38 km/sec if near an escape orbit. According to Shoemaker *et al.* (*7*), the energy required to produce craters of this size is 10^{23} to 10^{24} ergs, and, if the minimum velocity is assumed, this means that the mass of the objects thrown 1000 km from Tycho was in the neighborhood of 10^7 or 10^8 tons. Possibly the lower field of the moon and less strong surface materials in Mare Cognitum as compared to the earth would lower these estimated masses somewhat. However, it seems certain that if such large objects could be accelerated to 1 km/sec or more, objects as large as meteorites have been thrown from the moon and these would eventually arrive at the earth.

Gault (*8*) has argued that collisions of high-density objects with the moon would produce only fused silicate material with the escape velocity of the moon or greater. However, a comet head has hit the earth in this century; such collisions would be markedly different from solid-body collisions; and Gault specifically does not include such collisions in reaching his conclusion. It is well to keep in mind that comet collisions producing great masses of gas are a more probable mechanism for propelling these very massive objects from Tycho to Mare Cognitum. Lin (*9*) has shown that such collisions could accelerate objects to velocities considerably beyond the lunar escape velocity. Thus, considering all the evidence, some meteorites very probably come from the moon. It seems likely that, if these are of the chondritic type, then most of the stone meteorites come from the moon because of the polymict character, involving both chondrites and achondrites, and the rather consistent low cosmic-ray ages of both types, and that only rare types such as the eucrites, whose cosmic-ray age of around 10^8 years is similar to but still somewhat lower than the ages for iron meteorites, come from elsewhere. On the other hand, possibly only some odd types of meteorites come from the moon.

Carbonaceous Contaminants

During the last 3 years much information in regard to carbonaceous material in the carbonaceous chondrites has been reported. Particularly the Orgueil meteorite and other type-1 carbonaceous meteorites (*10*) have been studied. Some "organized elements" have been shown to be contaminants, but the more simple varieties are now regarded as indigenous to these objects. It has been shown that most of these are mineralized by oxides of iron, but also some by silicates (*11–13*). Also, after treatment by hydrochloric and hydrofluoric acids, residues remain that have the appearance of microorganisms of simple form and give absorption spectra in the near-ultraviolet similar to such spectra for recent terrestrial organisms (*12*). Absorption spectra of extracts indicate clearly that fatty acids are present in these meteorites (*11, 14*). Optical activity has been reported in saponifiable lipids and has been found to be levorotatory, in contrast to dextrorotatory samples prepared from probable contaminants by the identical procedure (*15*). The observed rotations are very small, and this measurement has not yet been confirmed. [Hayatsu (*16*) reports that he has not found optical activity, though the chemical procedures do not exactly duplicate those of the previous workers.] Also, present-day organisms growing in these objects may have destroyed one optical isomer and left the other. Hodgson and Baker (*17*) report the presence of vanadyl porphyrin and have presented evidence that it is not due to contamination during times much longer than the terrestrial sojourn of the Orgueil meteorite. Of the five bases present in deoxyribonucleic and ribonucleic acids, the presence of four has been reported (*14, 18*). Duchesne, Depireux, and Litt (*19*), using magnetic resonance techniques, have reported recently that Mighei and Nagoya (both type 2) contain high concentrations of free radicals up to 10^{17} per gram of carbon, and they conclude that such quantities are characteristic of biogenic material. It seems safe to say that if similar material were found on earth, no one would question its biological origin. Of course, life originated at some time from compounds of abiotic origin. These lines of evidence indicate that, if this is the origin of these compounds, quite interesting abiotic precursors of biological materials had appeared somewhere and the evolution toward viable primitive organisms was well started.

The Orgueil meteorite contained ammonium salts shortly after it fell (*20*) and still contains magnesium sulfate, free sulfur, and carbonates of magnesium, calcium, and ferrous iron (*21*). The first two are very soluble in water, and the carbonates are somewhat soluble. Carbonates and sulfates are present in sea water, and in the absence of free oxygen the ferrous ion and ammonium salts would also be expected to be present (*22*). The mixture of oxidized and reduced salts is somewhat puzzling, though it may be an equilibrium one as DuFresne and Anders (*21*) have shown. It may well be that ultraviolet light produced hydrogen peroxide from water and this produced the oxidized sulfur and carbon compounds as well as magnetite, which is also present. The composition of the Orgueil meteorite with respect to carbon compounds and these salts is consistent with what might well be expected to be present in the primitive oceans of the earth at a time during which primitive life was evolving from inanimate matter. The composition of the inorganic matrix of oxides of the elements is approximately that of solar material except that the gaseous and volatile compounds are absent, that is, the elemental abundances of nonvolatile elements and compounds are within a small factor, say 2 to 5, of the solar values. The mineral assemblage is that which is expected for rocks of igneous origin and approximate solar abundances and which has been subjected to water to produce hydrated silicates and oxidized iron, but which has not been sorted by running water.

Greenacre (*23*) has observed temporary red spots on the moon. The most reasonable explanation for these in my opinion is that advanced by Swings (*24*), namely, that ammonia escapes from the moon and is dissociated from NH_2 and H and that the amine radical fluoresces in the red as observed in comet tails. This is what would be expected if material like the Orgueil meteorite exists in the surface regions of the moon, since ammonium salts would be hydrolyzed by water and thus ammonia would escape. Of course, other sources of ammonia, such as nitrides, also would give a possible explanation if material like the enstatite-bearing meteorites were present.

Origin of the Moon

Agreement on the origin of the moon has not been secured. Only two possible origins are discussed today. (i) The moon may have escaped from the earth. Most students of the subject do not agree with this origin, but we discuss it nevertheless. In this case, some sedimentary rocks may be present on its surface, especially if this escape occurred some 10^9 years or more after the earth was formed. However, the escape process probably would have resulted in a breakup and mixing of surface materials with deeper terrestrial materials and must have been followed by an extensive collisional process. It would seem probable that the moon would have been contaminated with water and with biological material if the latter were present at the time of separation. The mineral composition of the lunar surface on the basis of this origin might well be that of the Orgueil or other carbonaceous meteorites.

(ii) The moon was captured by the earth. With many students, I prefer this hypothesis. Accounting for the capture of the moon from a heliocentric orbit by the earth is a difficult mechanical problem and probably would require the close approach of at least two bodies of approximately lunar mass to the neighborhood of the earth (*25*). I have proposed the presence of many such bodies in the solar system (*26*). In such an approach one would be lost from the system and the other captured. The one would return to a heliocentric orbit which would cross the earth's orbit. Arnold's calculations show that it would probably collide with the earth within some 10^6 or 10^7 years more or less. Also, other objects of similar mass were probably present at this time and were captured by the earth and other planets. Such a collision would produce fantastically violent events, with some materials possibly leaving the earth-moon system completely. But certainly some would be captured by the previously captured moon, and these would probably include both rocky materials and water. The violence of the process would certainly destroy much of any biological material that was present. However, only small amounts of viable biological material need escape high temperatures in order to inoculate the moon, and these would multiply rapidly in any temporary bodies of water. All details as to temperature distribution in such collisions are difficult to estimate in any case.

Either hypothesis would lead to contamination of the moon by terrestrial oceans to some uncertain extent and by some biological or prebiological material present at the time. I believe that this conclusion is valid, that the material of the Orgueil and related meteorites could be accounted for in this way (*27*), and that it is more reasonable to explore such possibilities before purely imaginative hypotheses that cannot be checked are considered seriously.

But if water were present on the moon, one may ask how much and for how long. Since river valleys or stream structures of any kind are not present on the moon, it seems certain that the amount was small and the time was short. Small effects of this kind could have been destroyed by the erosion processes shown to be present by the Ranger 7 pictures. Could it be that the comparatively smooth floors of the maria are the beds of ancient temporary lakes? Their smooth structure has led most students of the subject to assume that the maria are lava flows, and anyone not subscribing to this view is compelled to try to devise other explanations for this smoothness. The Ranger 7 pictures have made many people, including me, think seriously that Mare Cognitum consists of fragmented material rather than lava flow material. We must account for the crater Wargentin, which is full of smooth material to the brim. Could it be water or ice covered with some layer of dust and could it have become filled with water by temporary rains, and are its walls impervious to water while those of other craters are not? It has always seemed odd to me that the moon could produce hot lavas to fill Wargentin and at the same time be sufficiently rigid to support differences of 10 km in elevation of the lunar surface. Kopal (*28*) and Gold (*29*) have proposed that water has diffused from the lunar interior to fill the maria basins, and they compare this to water coming from the interior of the earth. However, water probably comes from the earth's interior through its numerous volcanoes and lava flows which have covered the original surface of the earth to a mean depth of some 15 km. Craig (*30*) finds that terrestrial hot springs consist mostly or entirely of meteoric and not juvenile water. It is difficult to believe that diffusion of water through rocky material either of the earth or moon would supply more than very limited quantities of water to their surfaces. Also the estimates of the amounts of water that have come to the earth's surface during geological time rest on very uncertain evidence. But these suggestions of Kopal and Gold have stimulated me to consider the possibility that contamination of the moon with water from the earth was larger than I intended to suggest previously. Only the Surveyor and Apollo missions to the moon can answer the questions raised in this way.

Many students of this subject believe firmly that meteorites of all kinds come from the asteroidal belt. We know nothing from direct observation in regard to the structure and composition of the asteroids. I believe that it is well to consider carefully the possibility that the moon is the origin of many of these objects. We have little information in regard to the asteroids, and this permits the imagination to construct all sorts of models with no limits imposed by direct observational data, which will probably not be available for some time. *Entia non sunt multiplicanda praeter necessitatem.* Why not think about the possibilities of an object nearby before we construct purely hypothetical physical properties for the asteroids?

Conclusion.

Considerable evidence of diverse kinds has accumulated during the last 6 years indicating that some or possibly most of the stone meteorites come from the moon. Included in these may well be the carbonaceous chondrites of the Orgueil type and this indicates that contamination of the moon with terrestrial water has occurred. This statement does not depend on the carbonaceous matter being of biotic origin. Models for the origin of the moon are consistent with the hypothesis that some contamination of this kind occurred. This conclusion is possible regardless of whether the meteorites come from the moon or not.

Note added in proof: E. Shoemaker has called my attention to two short lunar valleys sometimes with delta-like formation which may be residues of streams of limited duration, just as I suggested in this article. No generally accepted explanation for these valleys exists.

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