particles stood out sharply above the background in the data taken at the Stanford storage ring. After the team working at Stanford began tracking down the causes of inconsistencies in earlier experiments measuring the gross properties of the production of hadrons [*Science* **184**, 782 (1974)], they were quickly able to find the first new particle. For similar reasons, the discovery of the second particle was rapid. Experiments initiated with collisions of electrons and positrons are also well suited to measure the width of the resonance, which indicates how long the unseen particle lives. It was the team at Stanford that was able to establish that the new resonance was extremely narrow—probably less than 100 kev.

The new discoveries were not made with the world's most powerful accelerators. In fact, the Brookhaven AGS is the oldest accelerator in operation in the United States, though not the one with the lowest energy. The new particles are right in the middle of the mass range that can be studied with the AGS, and if sufficient motivation had been available in the past, the new particle might have been found sooner. At the Italian facility in Frascati, where the first electron-positron storage ring was built, the new particle could have conceivably been found 5 years ago.

Ironically, the Brookhaven AGS is running short of money just now, with funds for only 26 weeks of operation in this fiscal year, and the SLAC budget is also restricted. "We'll bend every effort to follow up the new discovery," says Ronald Rau of Brookhaven, "but we will run out of money in the not too distant future and have to quit. That's a shame because this is a hell of an exciting time."—WILLIAM D. METZ

# Exploring the Solar System (III): Whence the Moon?

Whether or not the moon has lost any of its popular mystique since man's footsteps have crossed its surface, its reputation among planetary scientists as an enigmatic object has grown rather than diminished as a result of the Apollo explorations. "Why is it," one geophysicist put it, "that the body with the most mysterious origin in the solar system dominates the night sky?"

The debate over the moon's origin continues unabated, with participants asserting in one form or another the hypotheses that the moon fissioned from the earth, was captured by the earth, or was formed along with the earth by accretion of smaller bodies. None of these mechanisms, alone or in combination, can yet be said to have been ruled out, and none is without serious objections. But the constraints for a theory of lunar origin are now somewhat clearer than before Apollo and there is increasing emphasis in recent work on the accretion hypothesis. The result is to focus new attention on the details of the accretional process and on a common origin for both planets and satellites. Indeed, rather than inquire why only the earth of all the inner planets should have a major moon, several investigators have turned the question around and are now asking why Mercury, Venus, and especially Mars do not.

That the moon is chemically quite different from the earth is now widely agreed. The differences are at once the major stumbling block for accretional theories (which imply that the moon was made in the same place and by the same processes that made the earth) and the major motivation for alternative hypotheses. Compared to the earth, the moon is enriched in refractory elements such as aluminum and uranium that condense at high temperatures, low in iron and nickel (the moon's metallic core, if there is one, is extremely small), and greatly depleted in volatile elements such as sulfur and lead.

Also constraining models of lunar origin are several pieces of information about the moon's geochemical history which are inferred from the Apollo studies. The entire body is thought to have been covered at one time with a layer of molten rock at least 100 kilometers deep in which the moon's original crust was formed. This crust apparently formed early in lunar history, no later than 4.3 billion to 4.6 billion years ago; and because of the cooling time required, the molten layer itself must have been formed in the first 100 million to 200 million years after the origin of the solar system. The accretion of material to form the moon must have effectively ended, it is thought, by the time the original crust had cooled, despite continuing heavy bombardment by meteoritic bodies for several hundred million years thereafter.

Geophysical constraints can also be inferred from the moon's orbital parameters and from the angular momentum of the earth-moon system. A puzzling circumstance is that the moon seems to be decelerating and receding from the earth at a rate that, if extrapolated back into the past, would imply separation of the two bodies less than a billion years ago, long after the formation of the youngest rocks found on the moon.

One proposed explanation is that tidal dissipation, which accounts for the deceleration, was lower in earlier times when continental configuration and climates were different. Estimates of the number of days in a month (a measure of the moon's distance from the earth) based on growth lines in fossil seashells seem to support a reduced dissipation in the past, but accurate data do not extend more than 0.5 billion years back in time. The moon's rapid deceleration thus appears to contradict the geochemical evidence for a more ancient origin and is not fully explained.

The various models of lunar origin all suffer the difficulty that the obvious explanations for the chemical differences between the earth and the moon are dynamically improbable, while the more dynamically acceptable mechanisms seem to offer little scope for chemical variability. Fission and capture models, in particular, seem to be favorites among investigators who are most concerned with explaining the chemical evidence. Others are prone to propose that the moon accreted in orbit around the earth (binary accretion models) on the basis of dynamical considerations without being able to explain just how chemical differences arose.

The possibility that the moon was once part of the earth and spun off due to rotational instability was first proposed by Darwin. A modern version of the fission hypothesis, due to D. U. Wise of the University of Massachusetts, proposes that when the earth was formed it was a homogeneous body rotating very rapidly but within the bounds of stability (with about twice the angular momentum of the present earth-moon system or a rotation period of about 2.6 hours). Subsequently the earth differentiated into a dense core and lighter mantle, reducing its moment of inertia and increasing its rotation rate until it spun off material to form a moon. Since this material would have come from the earth's metal-depleted mantle, this might explain the absence of a large metallic core on the moon. Other investigators have concluded that the known lunar rock types could be formed from terrestrial mantle material.

A variant of this model, proposed by A. E. Ringwood of the Australian National University at Canberra, assumes that the early earth was so hot as to boil off a thick atmosphere of metals and oxide vapors, which condensed as they were spun out into space by the rapidly rotating earth and eventually collected to form the moon. The chemical differences between the two are then due to the moon having, in effect, been distilled from the earth.

The major objections to the fission models appear to be dynamical. In particular, the assumption of such a rapidly spinning primitive earth in order to get fission in the first place is criticized by many planetary scientists. (None of the other planets spin at a rate near rotational instability at present.) Moreover, some mechanism must be postulated to dissipate this excess angular momentum later on and bring the earth-moon system into its present state. Also unexplained by this hypothesis is the inclination of the moon's orbit with respect to the earth's rotational axis, a circumstance inconsistent with a spin-off origin.

Recognition of the chemical differences between the earth and the moon has brought new interest in models that propose dissimilar origins for the two bodies, with the earth subsequently capturing the moon as a satellite. Implicit in this interest is the idea that there was some kind of chemical zoning in the solar nebula, with compositional differences between bodies formed at different distances from the sun. There is no agreement, however, as to where an object of the moon's composition should have formed.

Capturing a satellite, as it turns out, is difficult. Most investigators now agree that objects passing near the earth with high relative velocities (those in eccentric orbits reaching out as far as Mars or in as far as Mercury, for example) would be diverted into a new heliocentric orbit, not captured. Only objects approaching with slow relative velocities—those originating in a torus of space near the earth's orbit—can be captured. This constraint would seem to rule out the possibility that the moon was formed in some distant sector of the solar system (inside the orbit of Mercury, according to one proposal) and hence bar an explanation of the moon's composition on these grounds.

The dynamical constraints on capture have been worked out in considerable detail. If tidal friction between the two passing bodies is the capture mechanism, then their relative velocities at a great distance cannot exceed about 40 meters per second, according to W. M. Kaula of the University of California, Los Angeles. Even if the protomoon were to be fractured into pieces, some of which would be captured while others escape, the limiting velocity is still low, about 2.5 kilometers per second, according to J. A. Wood of the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts. Still higher velocity objects can be captured if they collide with planetesimals already in orbit around the earth, as proposed by Kaula, but this is in effect an accretional mechanism, since many of the previously captured planetesimals would also become part of the moon. Repeated encounters do not increase the chances of capture, according to V. S. Safronov of the Institute of Earth Physics, Moscow, but instead act on the average to increase their relative velocities, thus producing more eccentric or inclined orbits.

### Capture Models

Despite these constraints, a variety of capture models have been proposed. Some investigators, such as S. F. Singer of the University of Virginia, propose capturing the moon intact, while others, such as H. Alfvén and G. Arrhenius of the University of California, San Diego, envisage disruption of the moon in the process, with the present moon assembled from the fragments. D. L. Anderson of the California Institute of Technology suggests that the moon was formed in a highly inclined heliocentric orbit near the earth (from which it could be captured) from planetesimals that accreted later than those which eventually formed the earth. These late-forming planetesimals, Anderson believes, had a higher refractory content because more of their material condensed out of the solar nebula at some distance from the plane of the planets.

E. J. Öpik of Armagh Observatory in Northern Ireland proposes that a protomoon passed near the earth, was disrupted by tidal forces, and left part of itself to be captured. Wood and H. E. Mitler, also of the Smithsonian, have elaborated this model to suggest a series of such encounters, each of which stripped and retained in earth orbit the silicate mantles of the already evolved protomoons, thus building up material for a refractory moon. They find, however, that the process is very inefficient, requiring nearly an earth's mass of protomoons, and that the resulting fractionation may not be very great.

Still another version of the capture hypothesis assumes collision of one or more large planetesimals with the earth. W. K. Hartmann of the Planetary Science Institute, Tucson, Arizona, for instance, proposes that these collisions with an earth that had already undergone internal evolution might have ejected crustal and upper mantle material into earth orbit, where it eventually formed the moon. Since nature is not perfectly efficient, however, the impacting bodies must have had a total mass much larger than the moon's.

Taken together, the capture models seem to many planetary scientists to offer a more convincing explanation of the moon than do fission models, although there is considerable disagreement about any particular model. A major source of disagreement concerns the details of the accretional process that formed the moon, whether in earth orbit or elsewhere—in particular the size, time of formation, and composition of secondary planetary bodies formed in the region of space near where the planets themselves were forming. The debate over accretional processes is even more closely interwoven with the various binary accretion models that postulate a moon formed from a cloud of debris trapped in orbit around the growing earth.

Much of the research on accretional mechanisms has been done by Russian investigators, who postulate a small solar nebula from which the earth and other terrestrial planets formed over a period of about 100 million years (*Science*, 29 November). Collisions between particles approaching the growing earth would have left some of them in orbit around that body, gradually building up material from which the moon was to grow. E. L. Ruskol of the Institute of Earth Physics in Moscow estimates that destructive collisions with incoming objects would have prevented formation of the moon until the earth was about half its present size. Thereafter, she calculates, a moonlet might readily have formed.

This model works well when applied to the satellites of the major planets of the outer solar system, but it does not explain the size of the present moon or—since accretion over a period of $10^8$ years is too gradual to melt the outer layers of the moon—how it came to be heated. To overcome these limitations, Ruskol proposes that one or more large bodies were captured from heliocentric orbits, supplying the additional mass. Melting of the moon might have occurred, Ruskol points out, if several submoons formed first and then ultimately collided.

In contrast to this view, several American theorists propose that the terrestrial planets—and hence the moon—accreted much more rapidly from a larger nebula. Formation on a short enough time scale (1000 years for the moon) would cause extensive heating and melting from the rapid release of the kinetic energy of the incoming particles, not only for the moon but for many other planetary bodies as well. This emerging view of lunar origin (few explicit binary accretion models have appeared in the U.S. literature) is thus dynamically similar to the Russian version, except that the process occurs much more quickly. Kaula and A. W. Harris, also of the University of California, Los Angeles, do not favor rapid accretion but do propose that the embryo moon must have started early in the accretional process to have grown as large as it is.

Explaining the seemingly unique composition of the moon with binary accretion models is still the major difficulty, reflecting the complexity of the accretional process itself, although a number of possible explanations have been advanced. Among Russian investigators, the emphasis is on differences in the physical properties and history of the materials that formed the earth and moon. Ruskol, for example, proposes that high-energy collisions in the swarm of particles in orbit around the earth would have released volatile elements, which were then swept away by the solar wind. Similarly, silicate minerals are more susceptible to fracturing in collisions than metallic particles, and the resulting silica-rich small planetesimals and dust are more easily captured into earth orbit, she believes, than the large, metal-rich particles. These processes might well serve to make the moon rich in silicates and depleted in iron and volatiles, but some investigators believe they do not adequately explain the detailed chemical makeup of the moon.

In addition to these processes, proponents of the rapid-accretion scenario can also explain the moon's compositional differences from the earth by assuming that some chemical fractionation occurred within the solar nebula, which—in this view—may not have completely cooled before accretion began. Wood, however, points out that metallic iron and magnesium silicate, the two most abundant components, respectively, on the earth and the moon, condense at about the same temperatures, so it is difficult to attribute even gross differences to this process.

A further question about the binary accretion model concerns the consistency of its application to all the planets and satellites of the solar system. If the moon's formation is a natural consequence of the accretionary process, why don't other planets have moons of comparable size? Some parties to the debate argue that it is more plausible to assume a special circumstance for the moon than to invent reasons why several other planets do not have major satellites. Others argue that the collisional nature of the accretionary process inherently involves the statistics of small numbers—that the variety in satellite systems might in some cases simply reflect the differences between a violent collision with a large body, late in the accretionary process, and a near miss. In addition, several investigators have concluded that even large satellites of Mercury and Venus would probably have been destroyed by tidal forces from the sun. According to this point of view it is the tiny martian satellites that pose the real exception to the accretional model, and not the moon.

Even strong advocates of the binary accretion mechanism admit that the model, like fission and capture models, falls considerably short of a satisfactory explanation for how (and where) the moon came into existence. Certainly the accretional process is not yet well understood in detail. As a measure of the changing opinions on this matter, it is perhaps noteworthy that two recent reviews of lunar origins, one focusing on dynamics and the other on chemistry, both conclude that binary accretion currently looks to be the most promising mechanism. Thus the issue of the moon's origin now seems to be closely tied to the larger question of how the solar system was formed. At present, however, moonwatchers may gain a measure of satisfaction that the uniqueness of the earth's nearest neighbor remains intact.—ALLEN L. HAMMOND

**Additional Reading**

1. J. A. Wood, *Icarus*, in press.
2. W. M. Kaula and A. W. Harris, *Rev. Geophys. Space Phys.*, in press.

# X-ray Crystallography: A Refinement of Technique

Many scientists believe that a complete knowledge of the mechanism of action of enzymes and other proteins will not be possible without a detailed knowledge of the protein's three-dimensional structure. But the x-ray crystallographic determination of these structures at high resolution is a laborious, time-consuming, expensive process that does not always necessarily succeed. Within the last year, however, at least two new methods of handling x-ray data have appeared, and these promise not only to improve the facility with which high-resolution protein structures can be determined, but also to reduce the time and expense involved. These methods, which are in a sense similar to the data-processing techniques used to improve fuzzy television pictures from space vehicles, may not be a revolution in x-ray crystallography, but they are the next best thing to one.

The structure of a molecule can be uniquely specified by a set of x-ray diffraction intensities (structure factors) and phase angles that, in effect, define the spatial relation of the structural elements. A representation of the structure can be obtained by combining the structure factors and phase angles in a three-dimensional Fourier series to produce an electron density map. This mathematical process is analogous to the electronic process in which an FM radio receiver decodes a multiplexed monaural signal to produce a stereophonic program.

The phase angles, unfortunately, cannot be obtained directly from the experimental data, so some other way must be found to get at them. For