Making the Moon, Remaking Earth

It now seems likely that the impact of a Mars-size object somehow formed the moon; the effects of such a giant impact must still be reconciled with the present state of Earth

WHAT DO A MOONLIT NIGHT, the coming of spring, and the nickel/cobalt ratio of Earth's upper mantle have in common? They may all be the result of a catastrophic few hours in the early days of Earth history about 4.6 billion years ago. Researchers considering how the solar system formed from a ball of dust and gas have been driven to the conclusion that one of the last acts of creation was the collision of the partially formed proto-Earth with a body about the size of Mars. That catastrophe could have splashed enough debris into Earth orbit to form the moon and guarantee terrestrial lovers their moonlit nights. It could also have knocked Earth into its 23-degree tilt, ensuring the procession of the seasons.

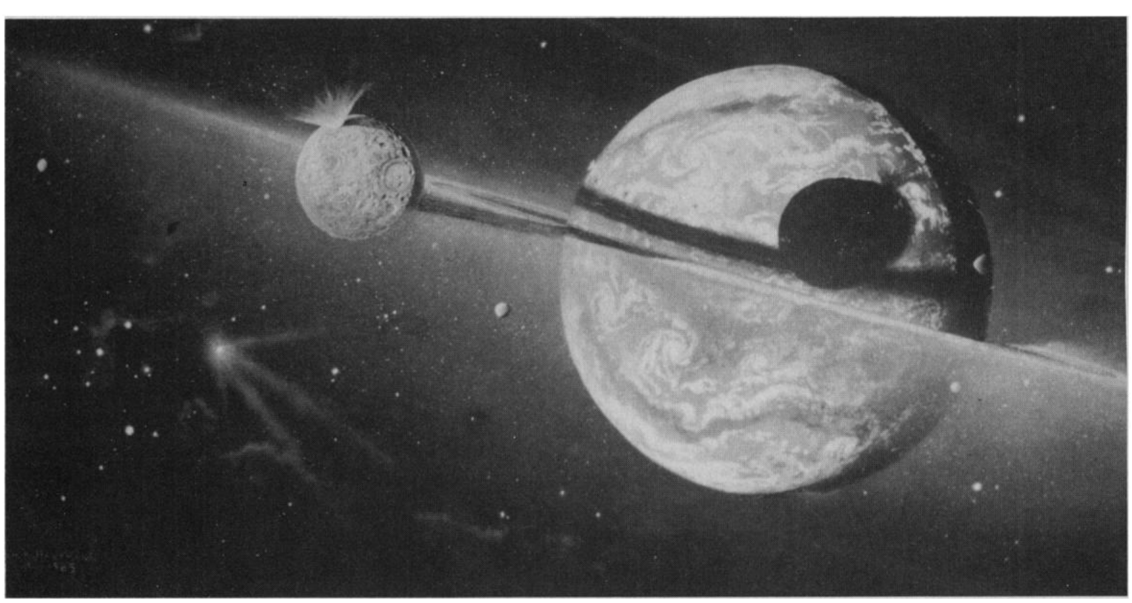
A giant impact would also have melted Earth through and through, which is where the composition of the upper mantle comes in. Some geochemists at a recent conference* on the origin of Earth contended that a giant impact and its inevitable melting of Earth do not jibe with what they know of geochemistry. In particular, the composition of the upper few hundred kilometers of the mantle implies that it has not been totally molten at any time, they said. The physicists considering how the Earth-moon system could have formed are optimistic that the geochemists will likely find some way around this apparent inconsistency.

It was the physics of the Earth-moon system that first catapulted the giant impact origin of the moon into prominence at a meeting in 1984 (*Science*, 30 November 1984, p. 1060). However the moon formed, figured dynamicists, the process had to account for the considerable amount of angular momentum represented in Earth's rotation and the moon's revolution about Earth. The three mechanisms that had been mulled over for more than a century seemed incapable of passing this angular momentum test. Spinning the proto-Earth until it fissioned into Earth and moon would produce plenty of angular momentum—too much, in fact. No one saw a way of getting rid of the fourfold excess. Capturing the moon as it whizzed by, the way a planetary probe would settle into orbit around Mars or Venus, would be highly improbable: the extremely slow approach speed required would imply a far greater likelihood of a collision or ejection. And forming a moon in orbit from the same hunks of agglomerated rock that formed Earth would not produce the needed angular momentum. Work since 1984 has only reinforced the cases against fission, capture, and coaccretion.

Enter the giant impact. Given the right combination of impactor mass and speed and an off-center hit, a giant impact could convey the right amount of angular momentum. It could also make some sense of the topsy-turvy solar system. If the rocky inner planets had accumulated grain by grain or even from 10-kilometer planetesimals, they would all orbit in exactly the same plane in perfectly circular orbits and they would not rotate. But as it is, Mercury is in a tilted, severely squashed orbit, Earth rotates rapidly at a tilt of 23.5 degrees, and Venus hardly rotates at all. Uranus is lying on its side. And Pluto is a mere chip of a planet in a wild orbit. If most of the solid material that was going to form the planets had agglomerated into relatively few lunar-size bodies, their banging into each other during the final steps of planet formation could account for such irregularity.

A good part of this agglomeration process, but not all of it, has been simulated in computer models. George Wetherill of the Carnegie Institution of Washington has modeled how 500 planetesimals, each having one-third the moon's mass, would behave. At this stage of the solar system's

*Origin of the Earth, held 1 to 3 December 1988, Berkeley, California. The conference was sponsored by the Lunar and Planetary Institute.



In the beginning. *Planetary scientist and artist William Hartmann has portrayed Earth soon after the giant impact hypothesized to have led to the formation of the moon. The debris splashed into orbit is still being swept up by the young moon. The Mars-size impactor would have melted Earth throughout.*

formation, a few bodies would have begun to dominate the process through their gravitational effects. This would have followed a time in which collisions between many small bodies, acting like a compressed gas, controlled the evolution toward planets.

In the simulations, a few planetesimals continued to grow at the expense of the others. Once a proto-Earth emerged, giant impacts were inevitable. In recent simulations of similar conditions, Wetherill found an average of three impacts on the proto-Earth by bodies having masses between those of Mercury and Mars. About one impactor on average had between one and two times a Martian mass, and one was even larger. The outcome of all this battering was two to six inner planets larger than the moon. That was reassuring, because the production of only four inner planets in the real solar system seemed to require that such broad gravitational sweeping by larger-than-average bodies had occurred.

These dynamical achievements alone have endeared the giant impact to those with a dynamical bent. But the hypothesis does more, as seen in the latest versions of the two computer models simulating the cataclysmic formation of the moon. They begin at a time late in the formation of the planets when the proto-Earth is the largest object and the Mars-size impactor—perhaps half the diameter of Earth and one-tenth its mass—is the next largest. They collide at, say, 11 kilometers per second, or 40,000 kilometers per hour. The tangential collision goes on for half an hour.

In both models, the impact appears to send enough material into orbit to form the moon. That is seen as an encouraging achievement, but the models are hardly in total agreement. "We're both getting a significant amount of material into orbit, but the implications are different," notes Jay Melosh of the University of Arizona, who with Marlin Kipp of Sandia National Laboratories is running one of the models. Theirs has 250-kilometer resolution that allows accurate simulation of gas jetting that boosts a plume of dense rock vapor into orbit. The plume is derived from both target and impactor. The model run by Willy Benz and Wayne Slattery of Los Alamos National Laboratory and Alastair Cameron of the Harvard-Smithsonian Center for Astrophysics has only 1000-kilometer resolution but it does calculate gravitational attraction among all its constituent parts. It is this ability that allows the model's deformed Earth to sling the rocky mantle of the impactor into orbit after the mantle separates from its iron core, which falls onto the proto-Earth and sinks to its center. Whether the new moon would actually have come from the impactor, the proto-Earth, or both is something geochemists are anxious to hear from the modelers.

One thing geochemists heard loud and clear from the modelers and physicists at the conference was that any giant impact must have melted Earth. Researchers have been considering for years whether the early Earth would lose the heat from a rain of impacting bodies fast enough to avoid reaching 1500°C and melting throughout into a so-called magma ocean. If the impactors were small, say less than a few tens of kilometers in diameter, the heat of impact would quickly radiate into space and Earth could avoid melting.

If you believe in giant impacts, you must believe in a melted early Earth.

But lately it has seemed harder than ever to keep Earth cold as it formed, giant impactors aside. At the meeting, Michael Gaffey of Rensselaer Polytechnic Institute pointed out that studies of asteroids now suggest that most, if not all, planetesimals were hot—near or above 1000°C—before they ever hit the proto-Earth. The loss of potential energy from the sinking globs of molten iron that formed the core would have heated the interior as well. And Takafumi Matsui and Yutaka Abe of the University of Tokyo have shown that if Earth accreted from a steady rain of smaller bodies, a dense steam atmosphere would have formed a greenhouse strong enough to trap the impact heat needed to form a magma ocean. There is no consensus on whether one or all of these processes melted the early Earth, but researchers agree that, at a minimum, they warmed proto-Earth throughout.

The message at the conference was that, if you believe in giant impacts, you must believe in a melted Earth. For one thing, the energy involved in a giant impact is enormous. Every bit of a Mars-size impactor hitting at the minimum velocity of 11 kilometers per second carries the energy of the same weight of TNT. And that energy is deposited throughout the proto-Earth, not just at the surface. Thanks to the huge size of the impactor, its shock waves would diminish by only a factor of 8 as they passed through the proto-Earth depositing impact energy along the way, notes Melosh. In the Melosh and Kipp model, the impact heats the mantle to 3000° to 4000°C. The mantle of the Cameron and Benz model heats to 5000° to 10,000°C. In Wetherill's simulation of the last 151 planetesimals in the inner solar system, the proto-Earth is totally melted by the time it grows to about 60% of its final size. "Giant impacts, I believe, inevitably cause global melting," says planetary physicist David Stevenson of the California Institute of Technology.

No one is claiming that giant impacts would not have melted Earth, but some of the geochemists at the conference were adamant about their failure to find any geochemical evidence for such melting. No magma ocean, they pointed out, would mean no moon-forming giant impact. The geochemical problem is that a magma chamber of any size does not simply freeze up like an ice cube. Different minerals freeze out first and either sink to the bottom or rise to form a surface scum or roof. That alters the composition of the remaining magma and thus the composition of minerals that form later.

Signs of such alteration seem hard to find. Michael Drake and his colleagues at the University of Arizona pointed out that such chemical fractionation should have increased the proportions of the element scandium to samarium, nickel to cobalt, and iridium to gold in Earth's mantle above those in the material that formed Earth. The assumption has been that this starting material was similar to chondrites, the most primitive of the meteorites. But Earth mantle ratios for these elements are approximately chondritic, Drake noted, suggesting little or no fractionation. A. E. Ringwood of the Australian National University extended this argument to a dozen or more different elements whose relative abundances should have been noticeably altered in the first crust formed on a molten Earth. He saw no evidence of such alteration in the earliest bits of terrestrial crust known. An observed anomaly in the abundance of the element europium in the earliest lunar crust relative to the lunar mantle has been taken as a sign that at least large parts of the moon had been molten. The giant impact hypothesis of Earth accretion and formation of the moon "is thus seriously flawed," Ringwood wrote.

Geochemistry would thus seem to be a potential stumbling block for the giant impact origin of the moon, but it may not be an insurmountable one. Bickering among geochemists at the conference over the significance of terrestrial as well as lunar geochemical data points up a lack of agreement in the field 20 years after the first Apollo mission returned samples from the moon. Some observers took the contentiousness as a sign that geochemical constraints may not be as rigorous as some geochemists would suggest.

There are also suggestions of ways around apparent geochemical constraints. Stevenson notes that, at great depths within the magma ocean, the residual liquid and the new crystals might not have buoyancies that differ sufficiently to separate them, or the liquid might have sunk rather than risen. Chemical fractionation, but not physical separation, would thus occur so that bulk rock composition might not reflect the melting.

Brian Tonks of the University of Arizona and Melosh argued at the meeting that an abundance of motion rather than immobilization could have prevented physical separation. A magma chamber as deep as Earth's mantle would be vigorously stirred from top to bottom, they argued, because the vigor of the convection carrying heat to the surface depends sensitively on the size of the chamber. An ordinary chamber some kilometers deep is stirred convectively, but even millimeter-size crystals could settle out or float to the surface. Flows within a planet-scale chamber, on the other hand, would keep crystals even a meter across entrained in the flow. On a molten moon, such boulders would settle out, creating the observed europium anomaly. But in a molten Earth, Melosh says, the large drop from high pressures at the bottom of a magma ocean, where crystals would grow, to the upper magma ocean, where they would tend to dissolve, would limit crystal size and prevent their separation.

Among the dynamicists, these or other ways around the geochemistry seem like a good bet. "My attitude is that Earth was completely molten," says Stevenson, "and the answer lies somewhere in the dynamics." A number of geochemists are not beyond convincing. The moon's formation through a giant impact "is a very attractive hypothesis," says John Jones of the Johnson Space Center. There may after all be a way to avoid creating traces of a molten Earth or to erase them later, he says, but, for now, he "tends to go with the simplest hypothesis, that parts of Earth never melted, but I can't say it's true."

Geochemist Jeffrey Taylor of the University of New Mexico sees the giant impact hypothesis as the leading contender, but he cautions that definitively testing it with geochemical data will be difficult. There are the uncertainties in the whole-body compositions of Earth and the moon as well as in the relative contributions to the moon from the proto-Earth and the impactor. And there is the composition of the impactor, a parameter that advocates are free to vary as needed.

All in all, the giant impact hypothesis is liable to maintain its bandwagon status thanks to its strong dynamical support, the absence of incontrovertible conflicts with observation, and the failure of all alternative explanations. ■ RICHARD A. KERR

Ice Age Art Idea Toppled

By dint of experimental simulation and microscopic observation, University of Turin anthropologist Francesco d'Errico appears to have laid to rest a once popular explanation of certain aspects of ice age art. The interpretation of prehistoric art necessarily is an intellectually hazardous exercise, particularly when the images under scrutiny are remote from what we know today. It is difficult enough to understand the role in prehistoric society of lifelike images of animals painted and engraved on cave walls and rock shelters: different social contexts can imbue the same images with different meanings. But when the art is in the abstract—sequences of arcs, lines, dots, and so on—the mind is stretched even further in search of explanations.

One of the most inventive explanations of these abstract images to have emerged in recent times was advanced by Alexander Marshack, an independent scholar in New York. Noting that many engravings on cave walls and portable art objects appeared to be the result of repeated application over an extended period of time, he made the following suggestion: "These indicate some of the probable origins of later formal systems, such as writing, arithmetic, and true calendrics, which emerge soon after the Upper Paleolithic." Rather than being artistic cascades of dots and dashes, or even Paleolithic doodles, these patterns represented, for instance, a lunar calendar or a kill tally through the hunting season, said Marshack. He extended the idea of repeated use of images to the representational forms in painting and carving, a notion that had a lot of appeal in the interpretation of art as an integral part of prehistoric life.

Recently, however, support for Marshack's hypothesis began to erode. For instance, Randall White of New York University concludes that aspects of engraved patterns that had been assumed to be the product of repeated application of different tools over a period of time could in fact be produced by a single tool in a single engraving event. "When you use a flint burin to engrave a piece of bone the cutting edge evolves quite quickly," he explained to *Science*. As the edge dulls or chips with use the cross section of the incision changes, often abruptly. "In this way lines produced by one tool can look as if they were produced by many."

White also points out that although it is easy to engrave fresh bone, very quickly the surface becomes hard. "At this stage engraving becomes very difficult, and the marks look very different from those done in the surface of fresh bone." From these observations, derived from experiments on fresh bone, White concludes that the patterns of dots, lines, and arcs found on prehistoric bone objects were probably the product of single engraving events, not the gradual buildup of marks over a long period of time. "There is plenty of room for doubt about Marshack's hypothesis," says White.

D'Errico's approach was similar to White's, but he analyzed incisions made on pebbles by people at the very end of the ice age, the so-called Azilian tradition. By first making incisions on several hundred limestone pebbles and examining them under various sorts of microscopy, d'Errico was able to identify tell-tale indications of lines made by one tool, by different tools, and over different periods of time.

Armed with this database d'Errico then scrutinized 122 Azilian pebbles, dating from 12,000 to 10,000 years ago, and from 30 different sites in France. "Whereas various other artifacts have been regarded as lunar calendars or notation systems," notes d'Errico, "these pebbles can certainly be considered the fullest, most uniform, and best-dated collection of objects for which such an interpretation has been proposed." D'Errico's task was to determine whether the cascade of marks on each of the pebbles was etched in one sitting or by repeated application over a long period.

"We found that they had always been made by rapid, repeated tool movements," says d'Errico. "One is thus tempted to conclude that prehistoric man was more interested in the overall result." If the patterns were created at one sitting and not over a period, then the suggestion of calendrics must be rejected. "One may reasonably ask whether the idea of Upper Paleolithic calendars does not spring from our projection of what we imagine prehistoric man was like, as opposed to examination of the evidence with minds free of wishful thinking." ■ ROGER LEWIN

ADDITIONAL READING

R. White, "The manipulation and use of burins in incision and notation," *Can. J. Anthropol.* **2**, 129 (1982).
F. d'Errico, "Paleolithic lunar calendars: a case of wishful thinking?" *Curr. Anthropol.* **30**, 117 (1989).