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Hot Idea

posted December 31, 1998

Origin of the Earth and Moon

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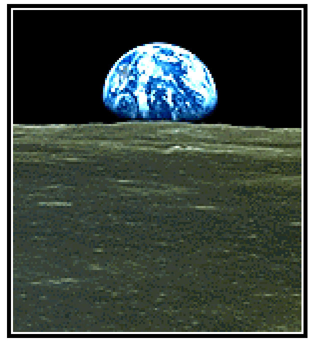


NASA

About 130 scientists met December 1-3, 1998, in Monterey, California, to share ideas about the formation and very early history of the Earth and Moon. Conference organizers constructed the program to allow time for participants to discuss crucial issues, leading to lively and spirited debate. The giant impact hypothesis for the Moon's origin still holds center stage. This idea suggests that the Moon formed as the result of a colossal impact onto the accumulating Earth, heating it and flinging the raw ingredients for the Moon into orbit around the Earth. The giant impact hypothesis is consistent with our ideas for how planets were assembled and explains some important features of the Earth-Moon system, such as why the Moon has only a tiny metallic core.

The isotopes of several elements in Earth and Moon rocks all point to the process of planet formation taking 50 to 100 million years. Planet formation involved many huge impacts, implying a molten (or mostly molten) primitive Earth. There are good indications that the young Earth was almost completely molten when it formed, but conference participants enthusiastically debated the extent of melting and the lines of evidence used to deduce it. Fortunately, there is an intense effort underway to understand the processes that might have operated inside the Earth during its birth, so the chemical evidence for or against the giant impact hypothesis may one day be acquired.

Reference:

Origin of the Earth and Moon, 1998, LPI Contribution No. 957, Lunar and Planetary Institute, Houston.

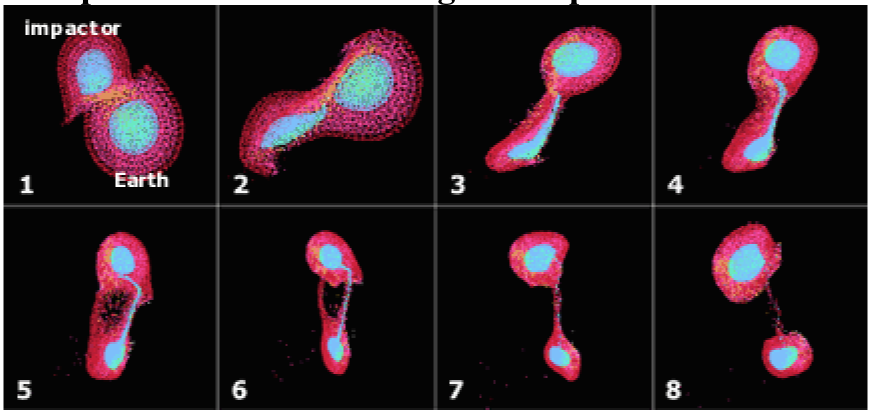
The Big Impact

The giant impact hypothesis exploded in popularity at a conference held in Kailua-Kona, Hawai'i, in 1984, though the fuse had been lit about ten years earlier. Two key papers had been published in 1975, one by William K. Hartmann and Donald Davis (Planetary Sciences Institute in Tucson, Arizona) and the other by Alfred G. W. Cameron and William Ward (Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts). Though they took different approaches to the problem, both suggested that the Moon formed when a huge impactor smashed into the Earth near the end of its construction. To account for the amount of angular momentum in the Earth-Moon system, Cameron estimated that the object would need to be about 10% the mass of Earth, about the size of Mars. (Angular momentum is the measure of motion of objects in curved paths, including both rotation and orbital motion. For the Earth and Moon this means the spin of each planet plus the orbital motion of the Moon around the Earth.)

Hartmann approached the problem from the perspective he had gained from studies of the history of lunar impact bombardment. He reasoned that if there were huge impact craters preserved on the Moon that were made by projectiles 150 km across, there must have been other gigantic projectiles, perhaps ten or more times larger. If one hit the Earth, Hartmann and Davis thought, perhaps sufficient material would be lifted into orbit to form the Moon. All four scientists also realized that big impacts fit into the picture of planet formation being painted by physicists studying how planets could have accumulated.

Such a monumental impact would cause a large amount of material to be lofted into orbit around the Earth, and the Moon could form from that debris. Cameron's recent research, done partly in collaboration with Robin Canup (Southwest Research Institute, Boulder), indicates that the immense moon-forming impact probably took place when the Earth was only about half constructed. If the Earth is too large, say close to its present size, formation of the Moon requires about twice the amount of angular momentum that the Earth-Moon system has now. An impact of the half-built Earth with an object a little over half its size could have formed the Moon and made the Earth about 2/3 complete. Most intriguing, the recent computer simulations indicate that the projectile hits, but much of it rebounds into a sub-orbital flight to hit the Earth again. The Earth and Moon continue to grow, by other large impacts, but not large enough to form another moon. What a violent beginning to our beautiful blue planet and the shape-changing light globe that decorates the night sky!

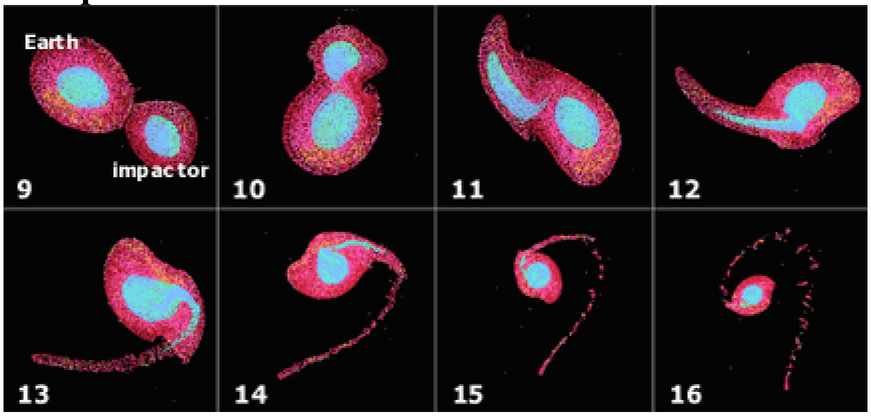
Computer simulations of a giant impact



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)

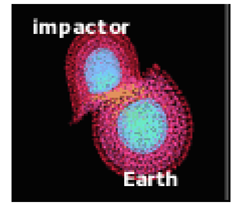
These pictures are snapshots of the formation of the Moon, as depicted by comuter simulations done by Al Cameron. Blue areas are metallic iron, and red and orange areas are rocky mantles. The growing Earth is the larger of the two objects; the smaller object is the projectile whose impact led to the formation of the Moon. In this simulation, the impactor hits off-centered (frame 1), and heats and deforms both bodies (frame 2). As the event continues, some metallic core (colored blue) is transferred to the Earth, but most remains inside the impactor. The impactor is not completely engulfed by the Earth and pulls away somewhat, as if it bounced off (frames 3-8). All this would have taken only about half an hour. (Changes in apparent size are due to changing the scale of the pictures in order to keep both objects in the field of view.)

Computer simulations continued



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)

16-frame movie



A.G.W. Cameron

The impactor now hits the Earth again (frame 9), but this time is incorporated into the Earth (frames 10-12). Its metallic core becomes part of Earth's core. Some rocky material is still left in orbit around the Earth (frames 13-16). The Moon forms from the debris left in orbit, most of which came from the impactor. The accretion of the material into the Moon is not shown in this simulation.

Al Cameron notes that there are numerous parameters still to test by computer simulations. He has not yet explored all the possibilities of the ratio of the mass of the growing Earth to that of the impactor, or the total range in angular momentum of the system. Jay Melosh (University of Arizona) points out that the physical properties (called the equation of state) he, Cameron, and others use in impact simulations is far from perfect and might lead to unrealistic results. Cameron agreed, noting that he "considers this game very primitive so far."

Accumulating Planets

The cloud from which the Solar System formed was composed of gas and dust. Somehow in that dusty cloud, the Sun formed in the center and the planets formed around it. The inner, rocky planets formed by accretion-they accumulated dust and rocks to become planets. As explained by Robin Canup at the conference, years of studying the physics of planet formation and countless computer simulations reveal three stages in the accretion of the planets. During the first stage, dust grains stuck to each other until objects were large enough to begin to attract material with their gravity fields, producing objects the size of asteroids (up to a few hundred kilometers in diameter).

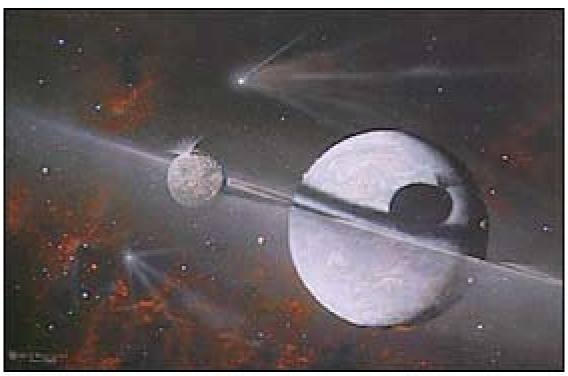

(Painting by William K. Hartmann. Used with permission.)

Inside the solar nebula, less than a million years after the sun formed, as depicted by scientist/artist Bill Hartmann. This shows the view in the region where the Earth will form. Small grains of dust are aggregating into planetesimals during stage 1 of planet formation.

During the second stage, a period of runaway growth took place, leading to tens of objects much larger than the Moon. Most of the mass of the inner Solar System was contained within these planetary embryos. It may have taken only about a million years from the end of stage 1 to the end of stage 2. During the final stage, these huge objects whacked into each other, creating larger planets, but a smaller number of them. The entire process was dominated by large impacts, making the formation of the Moon by a giant impact a natural consequence of planet formation. Whether a moon forms with each impact depends on the sizes of the two impacting objects and how off-centered an impact is. (Dead centered impacts do not give ejected material enough velocity to allow it to stay in orbit around a growing planet.) Simulations indicate that the third stage took 100 to 200 million years, about the time estimated from isotopic data on rocks from Earth, the Moon, and meteorites.

Assembling the Moon

A giant impact would lead to a ring of very hot debris in orbit around the young Earth. Calculations indicate that the Moon could have formed from that debris in ten years or less! This implies that the Moon would have formed very hot, possibly entirely molten. This scorching initial state is consistent with the idea that the Moon was surrounded by an ocean of magma when it formed. The magma ocean idea has been a central tenet of lunar science for decades, and recent data from the Clementine mission to the Moon finally proved it, as described in "Moonbeams and Elements," an October, 1997 **PSRD** article. The Moon probably continued to accrete material to it, including some objects up to about half its size. These big impacts could maintain a magma ocean, and scramble any crust that formed. It could also add rock with a composition different from the rest of the Moon, accounting for some unexplained features of the lunar interior.



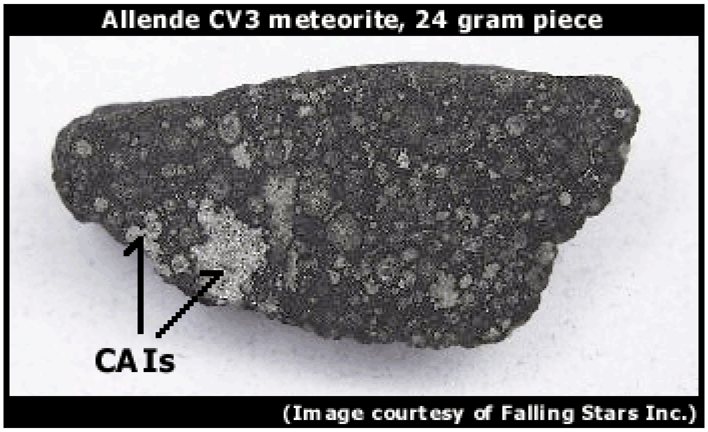
(Painting by William K. Hartmann. Used with permission.)

The moon is nearly completely formed in this painting by Bill Hartmann.

The existence of a magma ocean on the Moon is also prime evidence against the Moon forming by capture. Calculations show that if the Moon were captured, the process would not heat the Moon very much, certainly not so much that it would be mostly molten.

How Long Did Planet Formation Take?

The ages of the Solar System, the planets, and individual rocks on the planets can be determined from the abundances of isotopes of several elements. The basic principle is that a radioactive isotope decays to a stable isotope; the longer the time, the less of the radioactive isotope is present. For example, rubidium-87 decays to strontium-87. In some cases, the radioactive isotope has such a short half life (the time required for the abundance of the isotope to decrease by one half) that it no longer exists. Examples of such short-lived isotopes include aluminum-26 (half life of 700,000 years) and hafnium-182 (9 million years). The oldest materials that formed in the Solar System are inclusions rich in calcium and aluminum found within carbonaceous chondrite meteorites. Nicknamed CAIs (for **C**alcium-**A**luminum-rich **I**nclusions), these objects are thought to have been some of the first solids to form after the cloud of gas and dust began to heat up. CAIs have ages of 4.566 billion years. On the basis of measurements of several isotopes, the Earth and Moon formed about 50 to 100 million years later.



Calcium-aluminum rich inclusions (CAIs) are found in carbonaceous chondrites, like the Allende meteorite pictured here (53 mm-long sample). The white objects (arrows) are CAIs. They are the oldest materials to have formed in the Solar System. The Earth formed 50 to 100 million years after the formation of the CAIs.

Testing the Giant Impact Hypothesis

The initial temperatures of the Earth and Moon, the chemical compositions of their mantles, and the time when their cores formed in principle can be used to test the giant impact hypothesis. Unfortunately, planet formation and the subsequent formation of crusts, mantles, and cores is so complicated that much of the evidence may be destroyed. Furthermore, we do not yet have sufficient data to test all the possibilities. One of the most important predictions of the giant impact hypothesis is that the Earth should be mostly molten when it formed. This would have led to complete separation of elements that concentrate into metallic iron when the core formed. The composition of the Earth's upper mantle today suggests incomplete core formation or addition after core formation of a veneer of rocky material containing metallic iron. The problem is that the extent to which elements concentrate in metallic iron varies with pressure, temperature, and the amount of available oxygen and sulfur, and not enough experiments have been done to map out all those variables. On top of all that, the experiments are extremely difficult to do.

In addition, the continued growth of the Earth by large impacts might have led to episodes of magma oceans and core formation, not just one event. Each impact would not necessarily have led to a newly homogenized planet, either, as the impactors are thousands of kilometers across. It is not easy to thoroughly mix such huge masses of rock, even if molten. In fact, we do not know if Earth's lower mantle has the same composition as the upper mantle today.

The First Few Hundred Million Years of the Earth

Although not proven to everyone's satisfaction, the giant impact hypothesis explains a lot about the Earth and Moon. Combined with our current understanding of accretion, it leads to a dynamic and somewhat terrifying picture of the first few hundred million years for both bodies. The formation of the planets was a violent process. Huge rocky planetary embryos smashed into one another, forming oceans of magma surrounded by white-hot silicate atmospheres. Between the huge impacts, Earth's magma oceans probably cooled rapidly, perhaps in only a few years or decades. One such impact flung enough rocky stuff into orbit to form the Moon, which began its existence largely molten. Earth continued to be bombarded, forming new magma oceans. The impact rate declined and a stable crust formed on the Earth. Water and other volatiles, which may have been added late (perhaps in a giant impact), began to leak out to form oceans and the atmosphere. Eventually, the impact rate declined sufficiently so there were no more intense surface heating events, and life originated.

Additional Resources

Origin of the Earth and Moon, 1998, LPI Contribution No. 957, Lunar and Planetary Institute, Houston.

The Origin of the Moon website at the Planetary Science Research Institute.

Building Planets at PSI: the Origin of the Solar System website at the Planetary Science Research Institute.

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