Hot Idea

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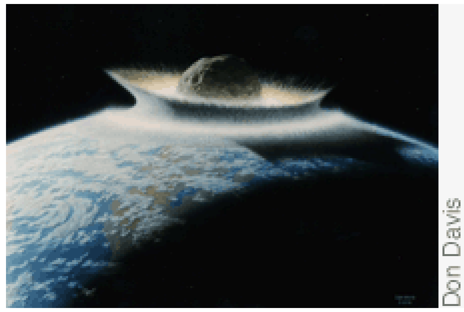

Lunar Meteorites and the Lunar Cataclysm

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The Moon has been pummeled with asteroids and comets throughout its long, 4.5 billion-year history. While even a single impact can be an impressive event, there seems to have been one particularly spectacular era about 3.9 billion years ago which saw the formation of 1700 craters 100 kilometers in size or larger, resurfacing 80% of the Moon's crust. This intense bombardment, known as the "Lunar Cataclysm," was first suspected nearly 30 years ago, based on the rocks returned by the Apollo astronauts. However, because the Apollo Moon rocks all come from a relatively small region on the Moon, many scientists worried that the effect was really just a local pounding.

In the December 1, 2000 issue of *Science,* my colleagues, Tim Swindle and David Kring, and I report that this intense bombardment is also reflected in lunar meteorites. Because lunar meteorites are a more random sampling of the Moon than the Apollo samples, the Lunar Cataclysm does indeed seem to have been a Moon-wide phenomenon. The Earth would not have escaped a similar beating during this time -- and neither would life on Earth.

Reference:

Cohen, B. A.,T. D. Swindle, D. A. Kring, 2000, Support for the Lunar Cataclysm Hypothesis from Lunar Meteorite Impact Melt Ages, *Science,* v. 290, no. 5497, p. 1754-1755.

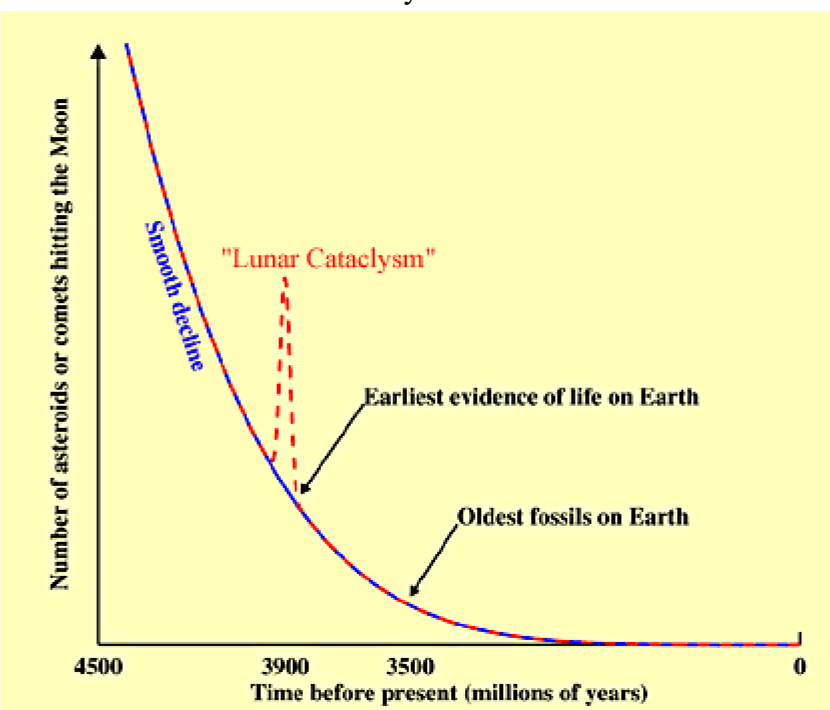
The Pummeled Moon

When you look up at the moon, the first thing you notice with your naked eye is the dark circles (maria) in a bright background (highlands.) When you look through even a small telescope, though, craters seem to pop up everywhere. In fact, the lunar highlands are saturated with craters, which means that if a new crater were to form, it would have to wipe out other craters because there is no empty space left. Craters come in all sizes, from micrometers to hundreds of kilometers in diameter. In fact, the dark maria are circular because they fill in the largest lunar craters, the basins. There are ~50 lunar basins, scars from extremely large impact events, that are each about the size of Texas.

The number of craters on a planetary surface is related to how frequently an impactor hits and the age of the surface. Older surfaces have more craters on them. At the beginning of the solar system, there was much more material available to be swept up than there is now, so the frequency of impacts might be expected to taper off with time. This would mean that very old surfaces have many more craters than young ones. At first glance, this seems to work out on the moon. The maria, which clearly came later than the highlands, have very few craters compared with the highlands.

Cratered highlands of the Moon. [NASA]

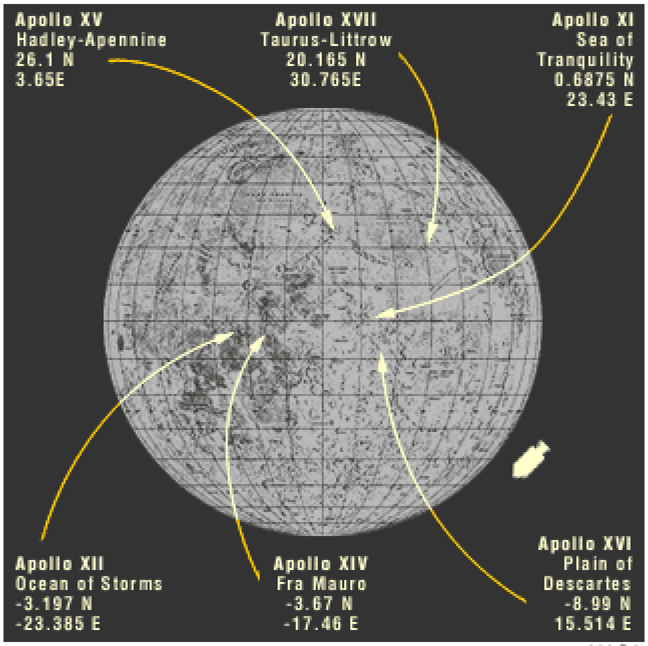
When the Apollo astronauts provided us with samples of the Moon's crust, scientists confirmed that the mare rocks are young (3.3-3.6 billion years) compared to rocks from the primitive lunar crust (4.5 billion years). However, the rocks affected by impact events yielded a surprise. If there were many more old impacts than young ones, then there should be many more old impact rocks than young ones. Instead, virtually all the impact rocks in the Apollo collection were roughly the same age, 3.9 billion years, and none were older. Scientists like Fouad Tera and Grenville Turner suggested that an unusual event must have occurred 3.9 billion years ago, a lunar cataclysm that created most of the large basins such as Imbrium as well as many smaller craters.



(Courtesy of B. A. Cohen)

The number of asteroids or comets hitting the Moon was much higher in the past, and tapered off with time (blue curve). Each impact affects the rocks it hits, so the number of impact rocks should be proportional to the area under the curve. A spike in the curve, labeled "Lunar Cataclysm," was proposed to explain the large number of rocks 3.9-billion years old.

However, the Apollo collection is a small sampling of rocks from a small area on the Moon. For the astronauts' safety, they had to land near the equator so that the command module could pass overhead every few hours, in case anything went wrong. Also, they had to land on the near side to maintain radio contact with the Earth. The six landing sites (and the three Luna landing sites from which robotic Soviet missions also returned rocks) are from a confined area on the Moon.



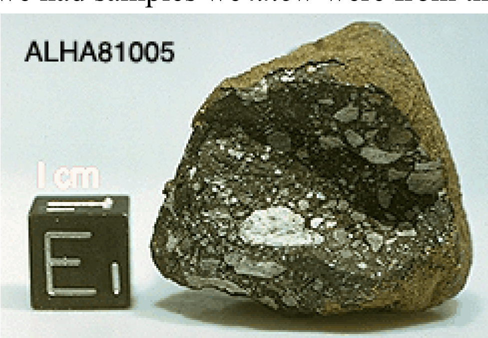
NASA

Every Apollo landing site is within or on the edge of a large lunar basin.

Remember, the basins are huge impact craters. It seemed possible that the Apollo samples were just pieces from these particular large basins, and the strange 3.9-billion-year ages were not representative of what was going on over the entire Moon. The best way to test for such a bias is to look at rocks from other places on the Moon, like the far side. The lunar meteorites fit this bill nicely.

Lunar Meteorites

The Moon rocks collected by the Apollo astronauts and the Soviet Luna probes are not the only rocks from the Moon that we have. We know that the Earth collects material from space all the time in the form of meteorites, although until we had samples we *knew* were from the Moon, scientists wouldn't have been able to identify a lunar meteorite.



NASA

On January 18, 1982, the ALHA81005 meteorite was found by the NSF meteorite reconnaissance team (ANSMET) in Antarctica.

When scientists studied ALHA81005 in detail, it bore so many resemblances to the Apollo and Lunar samples that they agreed virtually unanimously that it was from the Moon. They re-examined other meteorites and found three additional lunar meteorites already in our collections. Subsequently, more than a dozen other lunar meteorites have been found, mostly in Antarctica and the Saharan desert. [See listing of lunar meteorites.] These rocks are ejected from the Moon gently enough to remain intact for a journey through space and then a fiery passage through Earth's atmosphere.

Some of these meteorites are regolith breccias, formed when a chunk of regolith (the "soil," including all the rock fragments in it) is compressed into a single rock. So, these meteorites have many different pieces of the Moon's surface assembled into a single rock.

Since some of the fragments may be impact melts, within a single meteorite, there may be fragments of different impact rocks, dating different impact events. If you can show that the impact rocks don't come from the part of the Moon where the astronauts landed, this would be a good test of the Lunar Cataclysm idea. This was first suggested by G. Jeffrey Taylor at the University of Hawai'i when he examined the meteorite MAC88105. Jennifer Grier at the University of Arizona saw similar potential in another meteorite, QUE93069. Cohen saw DaG262 and DaG400 described at a meeting. While working on my PhD at the University of Arizona, Tim Swindle (my advisor, an expert in finding the ages of rocks), Dave Kring (an expert in studying the rocks formed in impacts) and I requested samples from these four meteorites to study.

To test the Lunar Cataclysm idea, the rocks had to be different from the Apollo samples and they had to come from large craters. We know now from Clementine and Lunar Prospector mapping missions that the Apollo sites are chemically unique in containing high abundances of a certain elements, including potassium (K) and phosphorous (P). The meteorites, on the other hand, are very low in K and P. Although no one knows exactly where on the Moon any of these meteorites come from, they don't come from the same place as the Apollo and Luna samples. To find rocks from large impacts, the group looked for "crystalline impact melts." It takes a fairly large impact to melt rock, but it takes an even larger one to create so much melt that some of it will be buried deeply and warmly enough to cool slowly enough to allow crystals to form.

This photograph is a view through polarized light of a thin slice (30 micrometers, about 1/1000 inch, thick) of a lunar impact melt. The irregular fragments are pieces of olivine and plagioclase crystals. The dark material that makes up most of the photo consists of small mineral fragments and tiny mineral grains that crystallized from an impact-generated magma. The photo shows an area 2 millimeters wide.

Dating Tiny Rocks

The impact melts satisfying these criteria were dated with a technique known as the ^{39}Ar-^{40}Ar method. It is based on radioactive decay, just as the well-known ^{14}C dating technique is. However, in ^{39}Ar-^{40}Ar dating, the radioactive isotope, ^{40}K, has a half-life of more than a billion years (as opposed to the 5700 years for ^{14}C), so it is possible to date things that happened billions of years ago, like the Lunar Cataclysm.

The element potassium is common in many rocks. On Earth, for example, it is found in the pink feldspar in granites. The Moon has feldspar too, and it also has K, though in low levels. Over time, the radioactive isotope of potassium, ^{40}K, decays to an isotope of argon, ^{40}Ar. Argon, like helium, is a noble gas, which means that it does not bond chemically to the minerals. However, an argon atom is a large atom and cannot easily leak out of a rock. So ^{40}Ar builds up inside. By measuring the amount of ^{40}Ar in a rock, and the amount of K which was available to produce it, scientists can calculate how long the ^{40}Ar has been building up - in other words, the age of the rock. The "^{39}Ar" in the name of the technique comes from using a nuclear reactor to convert some other potassium into the argon isotope ^{39}Ar, a technique pioneered by Grenville Turner in the 1960s, and used in early work on determining the ages of Apollo samples. The technique is sensitive enough that I was able to analyze tiny rock fragments less than a tenth of a millimeter long.

In testing the Lunar Cataclysm, we expected that if impact melt older than 3.9 billion years existed and was abundant on the Moon's surface, it was probable that we would find a piece of it among the four meteorites. Instead, we found no impact melts older than 3.9 billion years. This strengthens the idea that the Moon took a severe beating at around 3.9

billion years, and that it was Moon-wide. It seems that most of the current lunar surface acquired its visible craters in a short time, instead of gradually since the beginning of the solar system.

What could have caused the cataclysm? No one is sure yet. The most likely story may be that an asteroid broke up in the asteroid belt and was swept into the inner solar system. It would have had to be a very large asteroid, the size of the largest asteroids today. Alternatively, the gas giant planets Uranus and Neptune might have been still working to clear out solar system debris at this time, sending a shower of icy chunks to the Moon. Since the Moon is, and always has been, very dry, it seems unlikely that either the Uranus-Neptune objects or comets were responsible, since either one would have delivered a lot of water to the Moon.

How long did the Cataclysm last? Using the same ^{39}Ar-^{40}Ar technique on Apollo samples, Graham Ryder of the Lunar and Planetary Institute and G. Brent Dalrymple of Oregon State University have suggested that the Lunar Cataclysm may have lasted less than 100 million years.

What About the Earth?

Earth is a much bigger target than the Moon, so nearly 10 times as many impactors will hit the Earth. So, if the Moon was pummeled by 1,700 objects in 200 million years, the Earth got more than 17,000. This is a lot compared to the current flux. One crater the size of Chicxulub in Mexico (about 200 kilometers) is formed about every 100 million years now. The devastation and climate change associated with one Chicxulub crater helped wipe out the dinosaurs and many other species of life on Earth. What would it be like to have 17,000 Chicxulub craters in the same span? Furthermore, there would have been many craters much larger. Some would have dumped enough heat into the Earth's atmosphere to boil the oceans away. Perhaps that is why the oldest evidence we have for life on Earth is 3.85 billion years old - perhaps any life that got started before that was destroyed in the Cataclysm.

On the other hand, there are some forms of life that might not find it so bad. Single-celled organisms called hyperthermophiles (lovers of extreme heat) live in places like deep-sea vents and Yellowstone hot springs. These places are what the whole Earth might have been like as it was being pummeled, so these organisms might have survived or even have been quite happy. In fact, all life on Earth today seems to be genetically related to a hyperthermophile, so maybe these organisms survived and went on to populate the whole Earth, sort of like a microbial Noah.

Additional Resources

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