

Hot Idea

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Uranus, Neptune, and the Mountains of the Moon



--- The tardy formation of Uranus and Neptune might have caused the intense bombardment of the Moon 3.9 billion years ago.

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Huge circular basins, marked by low regions surrounded by concentric mountain ranges, decorate the Moon. The giant holes may have formed during a short, violent period from about 3.9 to 3.8 billion years ago. Three hundred to 1000 kilometers in diameter, their sizes suggest that fast-moving objects with diameters of 20 to about 150 kilometers hit the Moon. Numerous smaller craters also formed. If most large lunar craters formed between 3.9 and 3.8 billion years ago, where were the impactors sequestered for over 600 million years after the Moon formed?

One possibility has been studied with computer simulations by Harold Levison and colleagues from the Southwest Research Institute (Boulder, Colorado), Queen's University (Ontario, Canada), and NASA Ames Research Center in California. The idea, originally suggested in 1975 by George Wetherill (Carnegie Institution of Washington), is that a large population of icy objects inhabited the Solar System beyond Saturn. They were in stable orbits around the Sun for several hundred million years until, for some reason, Neptune and Uranus began to form. As the planets grew by capturing the smaller planetesimals, their growing gravitational attraction began to scatter the remaining planetesimals, catapulting millions of them into the inner Solar System. A small fraction of these objects crashed into the Moon and rocky planets, sculpturing the surfaces with immense craters. Calculations suggest that the bombardment would have lasted less than 100 million years, consistent with the ages of craters and impact basins in the lunar highlands.

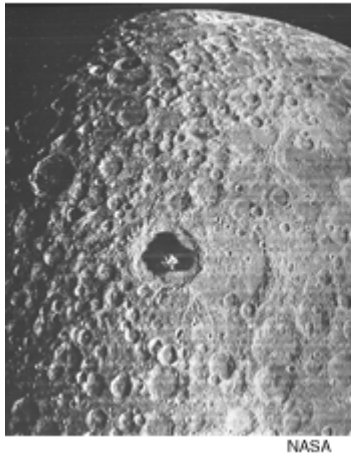
Reference:

Levison, H. F., Dones, L., Chapman, C. R., Stern, S. A., Duncan, M. J., and Zahnle, K. (2001) Could the lunar "late heavy bombardment" have been triggered by the formation of Uranus and Neptune? *Icarus*, vol. 151, p. 286-306.

Basins, Craters, and the Lunar Cataclysm

Except for their soft glow in reflected sunlight, there is nothing subtle about the highlands of the Moon. They are a cratered mess, a rubble pile where craters are more tightly packed than commuters at rush hour. There are thousands of craters tens of kilometers across, and about 45 that are larger than 300 kilometers in diameter. The largest is the South Pole-Aitken basin, 2500 kilometers across, the distance from San Francisco to Kansas City. This was a blitzkrieg.

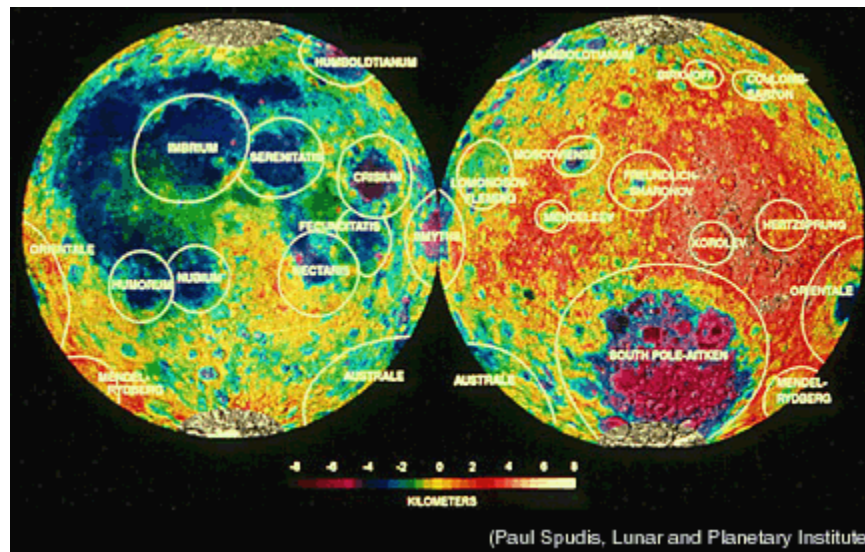
Cratered Highlands



Orientale Basin



Impacts of large, fast-moving projectiles have sculpted the lunar highlands, as shown on the left. The large crater in the center is Tsiolkovsky, about 180 kilometers in diameter. It is flooded with dark mare basalt lava flows. Tsiolkovsky sits in an older, larger crater called the Tsiolkovsky-Stark basin, which is about 700 kilometers in diameter. About 45 craters on the Moon are larger than 300 kilometers across; lunar geologists call these basins. The prominent ring of the Orientale Basin (right) is 930 kilometers in diameter and marks the highest rim of the basin. [Click on image for a high-resolution version.]



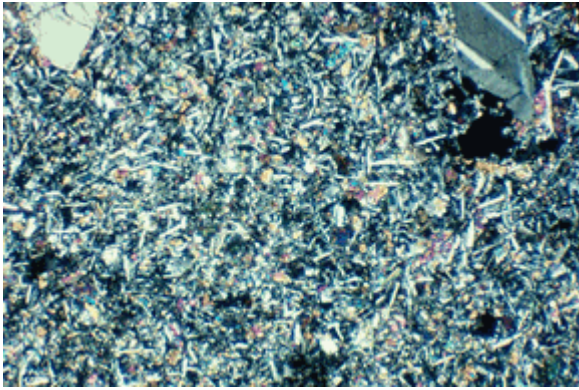
This topographic map obtained by the Clementine mission shows some of the most prominent basins on the Moon. [Click on the image for a high-resolution version.]

When did all these craters form? Almost all are clearly older than the lunar maria, which fill low spots in the big basins and contain far fewer craters. The maria have ages younger than about 3.8 billion years, so the intense bombardment of the highlands and the formation of the basins took place before that. Some lunar scientists believe that the bombardment took place between 4.5 billion years (when the Moon and planets formed) to 3.8 billion years. In this view, the bombardment rate decreased drastically from 4.5 to 3.8 billion years ago. Experts in the formation of planets from swarms of planetesimals tend to favor this idea. The leader of this school of thought is William Hartmann (Planetary Science Institute, Tucson).

An alternative view holds that the impact rate declined very rapidly soon after the Moon formed, but then increased dramatically during a short interval between about 3.9 and 3.8 billion years ago. This idea, dubbed the "lunar cataclysm," was first proposed by Fouad Tera and Gerald Wasserburg (Caltech) in 1975 on the basis of the ages of

rocks returned by astronauts from the lunar highlands. The idea suffered benign neglect until Graham Ryder (Lunar and Planetary Institute) revived it in 1990 and has since found additional evidence for it among Apollo samples. The ages of melted chunks of rock in meteorites from the lunar highlands also seem to favor a sharp cutoff at about 3.9 billion years. [See PSRD article: [Lunar Meteorites and the Lunar Cataclysm](#).] So, many scientists specializing in the analysis of lunar samples believe this story. (Many, not all. There are naysayers, as explained below.)

To test the idea of the lunar cataclysm we must determine the ages of the large basins. To do this we need samples whose ages were completely reset by the impact that blasted out a specific basin. The only samples we can be sure were reset are those that were melted during the impact. Unmelted samples retain a memory of their pre-impact origin, so cannot be used. In fact, most of the material tossed out of a growing crater, although fractured and partly pulverized, is not even heated enough to reset rock ages at all. We need impact melts. And we need them from impact basins.



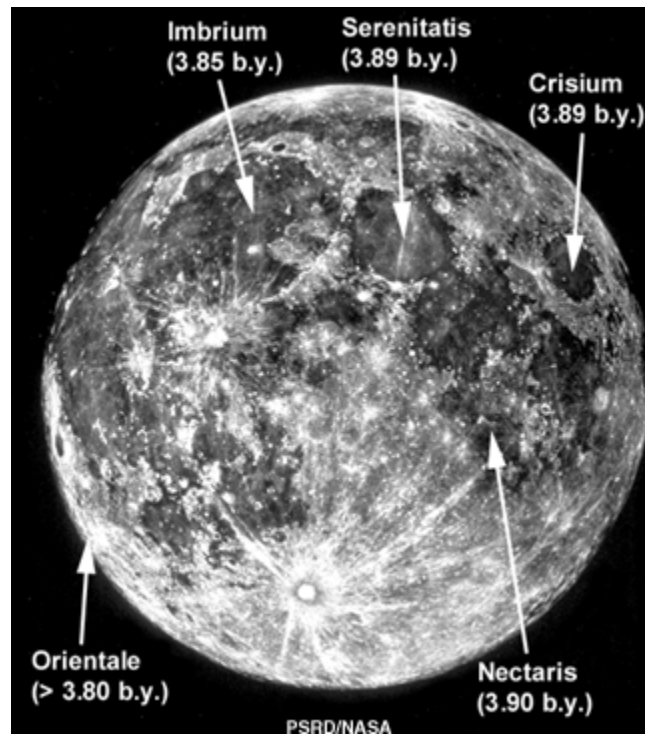
Ancient impact events can be dated only by finding pieces of rock that were melted during the formation of a crater or basin. This one from the Apollo 16 site helps date the Nectaris basin. The photo, 2.9 millimeters across, was taken in polarized light, giving false colors diagnostic of the minerals in the rock. The gray to white one is plagioclase feldspar. The lath-like shapes of the feldspar crystals provide unambiguous evidence for crystallization from molten rock.

We can use the number of craters on a planetary surface to determine relative ages. Crater counts allow us to safely say that all the maria are younger than the Orientale basin, the youngest and freshest of the great impact basins. The oldest mare rocks are 3.80 billion years. Thus, all impact basins are older than that age.

The Imbrium basin is older than the non-mare lava flows of the Apennine Bench Formation, which samples from the Apollo 15 mission show formed 3.84 billion years ago. (The uncertainty in the age is plus or minus 0.02 billion years. This means that the age of the lava flows of the Apennine Bench Formation is somewhere between 3.82 and 3.86 billion years.) Impact melts from the Apollo 14 and 15 missions can be used to date the Imbrium impact, although none can be proved to have been produced by the event itself. Nevertheless, they were collected in the debris pile thrown out of Imbrium, so either were formed by the event or existed before it. These ages, determined by Brent Dalrymple (Oregon State University) and Graham Ryder (Lunar and Planetary Institute) suggest Imbrium formed 3.85 billion years ago (give or take 0.02 billion years).

Samples of impact melt collected during the Apollo 17 mission allow Dalrymple and Ryder to date the Serenitatis basin, as the Apollo 17 landing site is inside that basin. Those ages are 3.893 (plus or minus 0.009) billion years, clearly older than Imbrium. The Luna 20 mission landed on the rim of the Crisium basin. It returned lunar regolith (soil), so the samples are all small rock fragments. Nevertheless, analytical capabilities are so good that we can determine the rock type from microscopic study, the bulk chemical composition, and the age on a little rock only a millimeter or two across. Those ages, determined by Tim Swindle (University of Arizona) and colleagues, came out to be 3.85 to 3.90 billion years. The best guess is that Crisium is somewhat less than 3.90 billion years old, perhaps 3.89.

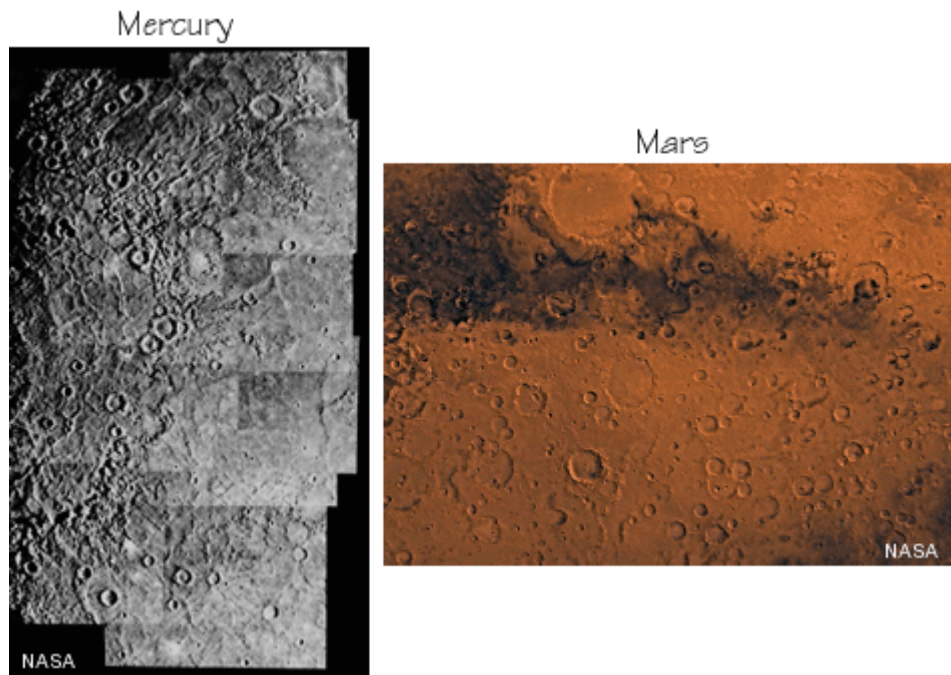
Apollo 16 landed on ejecta from the Nectaris basin. One group of impact melt rocks at the site is considered by many lunar scientists to have been produced by the Nectaris impact. Those rocks have ages of less than 3.92 billion years. Graham Ryder argues that the age of Nectaris is likely to be about 3.90 billion years. All these ages indicate that the five dated basins formed between 3.9 and 3.8 billion years ago. In addition, by noting which basins deposited debris on other basins, we can determine the relative ages of lots of basins. Using that geologic data, it is clear that at least seven other basins formed during the same time interval. It is possible that most--maybe almost all--lunar basins formed during that short time interval. As G. J. Wasserburg said in a talk at the Lunar Science Conference in 1975, "It must have been a hell of a show to watch!"



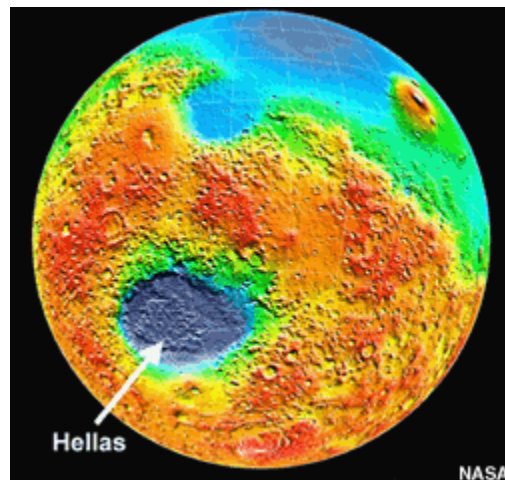
The ages of five basins on the Moon have been determined. Other basins are known to be younger than Nectaris and older than Orientale, so at least 12 basins formed between >3.80 and 3.90 billion years ago. Possibly almost all 45 lunar basins formed during this time period.

As usual in science, not everyone agrees. Larry Haskin (Washington University in St. Louis) and others argue that the impact that blasted out the Imbrium basin distributed materials very widely and reset ages all over the place. The result, they argue, is that the narrow interval of less than 100 million years is only apparent. We are dating just the Imbrium event. Most of us do not agree with this point of view. We point out that the chemical compositions of the impact melts vary from landing site to landing site. More important, the ages are distinguishable from one another—there is a genuine age difference between the rocks collected at Apollo 14 and 15 (Imbrium) compared to those at Apollo 17 (Serenitatis), Lunar 20 (Crisium), and Apollo 16 (Nectaris). We will not resolve this debate until we get more samples from lunar basins. In the meantime, we'll argue with each other.

The Moon was not the only object bombarded long ago. The ancient surfaces of Mercury and Mars are cratered severely, with many multi-ring basins. Did the same population of objects that pummeled the Moon also dig up the surfaces of Mercury and Mars? In fact, what about the heavily cratered surfaces of the icy satellites of Jupiter and Saturn? (Venus and Earth are too active geologically to have preserved much of a record of the early bombardment. There are rocks older than 3.8 billion years on Earth and some investigators are trying to use them to understand the early bombardment of the Earth.)



The surfaces of Mercury (left) and Mars (right) show the same kind of circular scars as the Moon. The Caloris basin, 1300 kilometers in diameter, on Mercury dominates the left half of the photograph. Numerous craters are visible in the image of Mars, including the basin Schiaparelli (400 kilometers in diameter), located in the top center of this Viking mosaic. Planetary scientists agree that these basins are very old, but their precise ages are unknown.



The huge Hellas basin is clearly visible on this topographic map of Mars, in which blue is low and red represents high elevations. Hellas is almost 2000 kilometers in diameter.

Uranus and Neptune: Late Bloomers

There was nothing gentle about planet formation. Dust grains glommed together, making clumps. The clumps stuck together to make big chunks, 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). This led to a period of runaway growth in which tens of objects much larger than the Moon formed. Finally, these huge objects whacked into each other, creating larger planets, but a smaller number of them. The entire process was dominated by large impacts.

The accretion of the planets swept up much of the debris, so it is logical to expect that the impact rate on a given planet would decrease with time. In the case of the Moon, ages of impact melts should cluster towards the time when the impact rate was highest--right after the Moon formed 4.5 billion years ago. Instead, the ages cluster around 3.9 billion years. What gives?

Imaginative planetary scientists have proposed several explanations for the dramatic increase in the impact rate at about 3.9 billion years ago. One is the leftovers model. This idea proposes that there were a lot of small bodies left over after the formation of the inner planets, enough to make about a Moon's worth. They were swept up fairly rapidly, but there might have been enough left over to do a lot of planetary pummeling about 3.9 billion years ago.

Another idea is that a large asteroid broke up and the fragments showered the inner planets. This requires the break up of a hefty asteroid, one as large as the largest surviving asteroid, Ceres (about 1000 kilometers in diameter). Objects that big are difficult to bust apart. Others have suggested that a passing star could have disturbed the orbits of comets in the Oort cloud, the vast collection of comets far beyond Pluto, and sent them zipping through the solar system. And then there's the delayed formation of Uranus and Neptune, an idea proposed originally in 1975 by George Wetherill (Carnegie Institution of Washington).

Harold Levison and his coworkers have begun a series of detailed studies of all these ideas. They begin with the late blooming of Uranus and Neptune. Now you would think that if huge planets were going to form, they would do so early, when we think the inner planets, Jupiter, and Saturn formed. Computer calculations, in fact, predict formation times of about 100 million years--but not for Uranus and Neptune. The problem is that the part of the solar system where Uranus and Neptune now reside was populated by small bodies that were widely spaced. This made it difficult for them to attract each other. Closer to Jupiter and Saturn, however, there were more objects available for planet construction. One controversial idea developed by Levison and his colleagues Edward Thommes (Queen's University, Ontario) and Martin Duncan (Southwest Research Institute, Boulder) is that Uranus and Neptune formed in the region of solar system where Jupiter and Saturn formed, and then were scattered outwards by the immense gravity fields of the gas giants. They end up in their present locations, ready to fling planetesimals towards the inner solar system.

Scientists understand so little about the formation of Uranus and Neptune that Levison states, "...the possibilities concerning the formation of Uranus and Neptune are almost endless." That being the case, their delayed formation or their transport from near Jupiter and Saturn are as likely as their early formation in their present locations. So, Levison and his colleagues assume that the two planets formed 600 million years after the beginning of the solar system, and examined whether their assembly caused impacts in the inner solar system.

Let's set the stage. In the story examined by Levison and coworkers, in the early solar system the planets ended at Saturn. Beyond Saturn there was nothing but a huge number of cold, icy planetesimals in orbit around the Sun. After 600 million years or so, something causes some of them to accrete to a couple of larger objects. This causes a rapid growth of the objects, eventually making Uranus and Neptune. Their large gravity begins to alter the orbits of the remaining planetesimals. Some are flung outwards, others inwards. A small percentage of those hurled inwards smack into the icy satellites of Saturn and Jupiter, and into Mars and the rest of the inner planets, including the Moon.

Their calculations indicate that the scattered planetesimals would have bombarded the inner solar system for only a few tens of millions of years--the duration of the lunar cataclysm. The calculations also indicate that only one in about 100 million of the scattered objects hit the Moon. This means that there must have been a lot of material in the region where Uranus and Neptune formed, about 30 Earth masses worth. Most models of the solar system indicate that there was at most only 50 Earth masses way out there, consistent with the calculations. The whole process also scatters asteroids, which add to the impacting population in the inner solar system.

Testing the Late Arrival of Uranus and Neptune

The overdue birth of Uranus and Neptune seems to provide a satisfying explanation for the spike in the bombardment

history of the Moon. However, before we declare this case closed, some additional tests need to be done. One is to determine the ages of more lunar basins. Dating impact melt rocks inside lunar meteorites, as Barbara Cohen and her colleagues have done is a good start. [See **PSRD** article: [Lunar Meteorites and the Lunar Cataclysm](#).] An even better way would be to collect samples from the floors of large basins on the Moon. This could be done with automated sample return missions.

It is also crucial to determine the ages of basins on Mars. This, too, will require samples to be returned to Earth because it is impossible to make age measurements remotely to the precision and accuracy needed to see if the basins formed between 3.8 and 3.9 billion years ago. Ages from Mercury would be helpful, too, but sample returns from that planet are very difficult. Returning a sample to Earth requires a gigantic, expensive rocket to blast away from the nearby Sun's huge gravity field.

Detailed studies of the satellites of Jupiter will also be important. Levison notes that about 500 basins would have formed on Callisto, the second largest of Jupiter's satellites. The heat generated by the impacts would have melted the surface to a depth of perhaps 150 kilometers, possibly erasing almost all of the basins. The fact that there are only four basins known on Callisto is consistent with the late formation of Uranus and Neptune, but more detailed studies of all the icy satellites need to be done.

It will be equally important for those studying how planets form to develop consistent stories for the formation of Uranus and Neptune. Levison and colleagues conclude their paper by noting: "the model presented in this paper must be viewed with skepticism until formation models of Uranus and Neptune are available that are consistent with this late arrival." It seems certain that scientists will view it all skeptically!

The study of the bombardment history of the Solar System is fundamental to understanding the formation of the planets and their early histories. It also requires an interdisciplinary approach. The bombardment history of each planet and moon must be worked out from geological studies and analyses of samples returned from them. All those data can then be used to test the calculations done by scientists like Levison and his coworkers.

[Additional Resources](#)

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