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Wandering Gas Giants and Lunar Bombardment

--- Outward migration of Saturn might have triggered a dramatic increase in the bombardment rate on the Moon 3.9 billion years ago, an idea testable with lunar samples.

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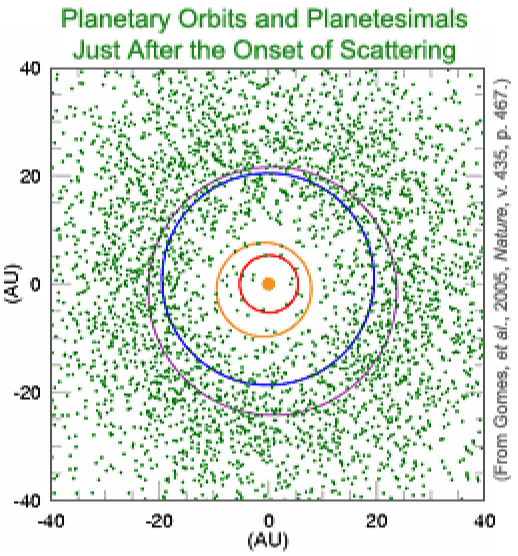


Planetary Orbits and Planetesimals Just After the Onset of Scattering

(From Gomes, et al., 2005, *Nature*, v. 435, p. 467.)

There may have been a dramatic event early in the history of the Solar System--the intense bombardment of the inner planets and the Moon by planetesimals during a narrow interval between 3.92 and 3.85 billion years ago, called the late heavy bombardment, but also nicknamed the lunar cataclysm. The evidence for this event comes from Apollo lunar samples and lunar meteorites. While not proven, it makes for an interesting working hypothesis. If correct, what caused it to happen?

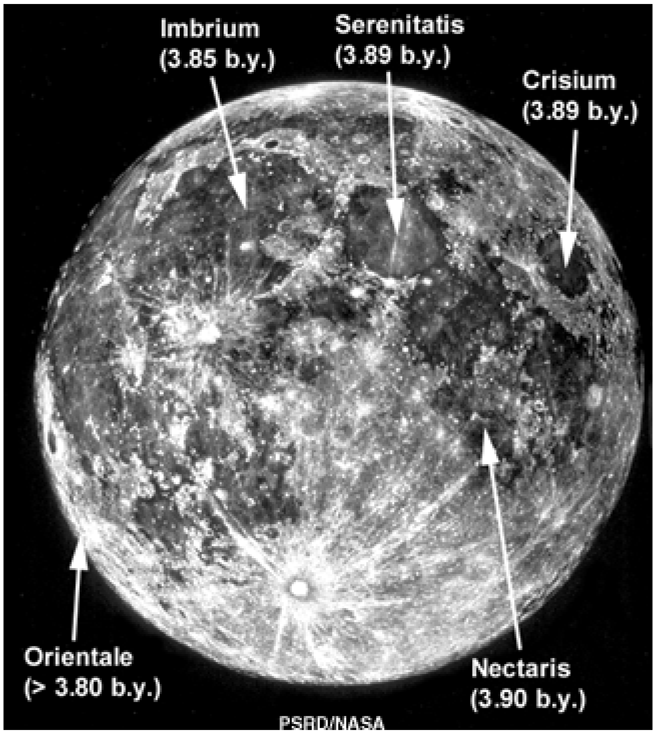
A group of physicists from the Observatoire de la Côte d'Azur (Nice, France), GEA/OV/Universidade Federal do Rio de Janeiro and Observatório Nacional/MTC (Rio de Janeiro, Brazil), and the Southwest Research Institute (Boulder, Colorado) conducted a series of studies of the dynamics of the early Solar System. Alessandro Morbidelli, Kleomenis Tsiganis, Rodney Gomes, and Harold Levison simulated the migration of Saturn and Jupiter. When the orbits of these giant planets reached the special condition of Saturn making one trip around the Sun for every two trips by Jupiter (called the 1:2 resonance), violent gravitational shoves made the orbits of Neptune and Uranus unstable, causing them to migrate rapidly and scatter countless planetesimals throughout the Solar System. This dramatic event could have happened in a short interval, anywhere from 200 million years to a billion years after planet formation, causing the lunar cataclysm, which would have affected all the inner planets.

References:

- Tsiganis, K., R. Gomes, A. Morbidelli, and H. F. Levison (2005) Origin of the orbital architecture of the giant planets of the Solar System. *Nature*, v. 435, p. 459-461.
- Morbidelli, A., H. F. Levison, K. Tsiganis, and R. Gomes (2005) Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature,* v. 435, p. 462-465.
- Gomes, R., H. F. Levison, K. Tsiganis, and A. Morbidelli (2005) Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature*, v. 435, p. 466-469.

The Lunar Cataclysm

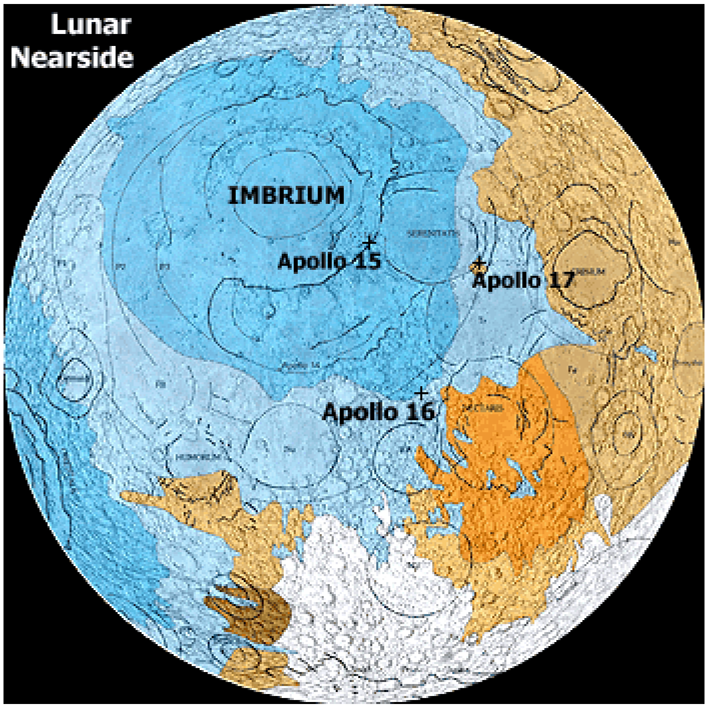
There are lots of really old lunar rocks. Ferroan anorthosites, which were the first to accumulate from the ocean of magma surrounding the Moon when it formed, crystallized 4.45 billion years ago (see **PSRD** article The Oldest Moon Rocks.) However, many, many rocks formed by melting during huge impact events, which we call "impact melt breccias," have ages that fall into a narrow time interval, between 3.92 and 3.85 billion years. This apparent clustering of ages was first noticed in the mid-1970s by Fouad Tera, Dimitri Papanastassiou, and Gerald Wasserburg (Caltech) who concluded that the ages record an intense bombardment of the Moon. They called it the "lunar cataclysm" and proposed that it represented a dramatic increase in the rate of bombardment of the Moon around 3.9 billion years ago. More recent work on lunar samples and lunar meteorites generally confirms that there is a dearth of ages for impact melts older than 3.9 billion years (see **PSRD** article Lunar Meteorites and the Lunar Cataclysm.)



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.

The Cataclysm Skeptics Club

The lunar cataclysm is an established, solid idea. Or is it? No, say the voices from the critics' corner. Randy Korotev (Washington University in St. Louis) is skeptical of the whole idea, as was his late colleague Larry Haskin. Korotev thinks we have a hideous sampling problem, and that the Apollo sites were all too close to the Imbrium impact basin. Imbrium is 1300 kilometers in diameter and tossed its continuous ejecta over an area twice that size; see image below. (The basalt flows composing Mare Imbrium make up a thin veneer that covers only part of the impact basin.) They say that all the impact melt breccias we have are associated with the Imbrium impact. No wonder they all have the same age--they were all made by one gigantic event.

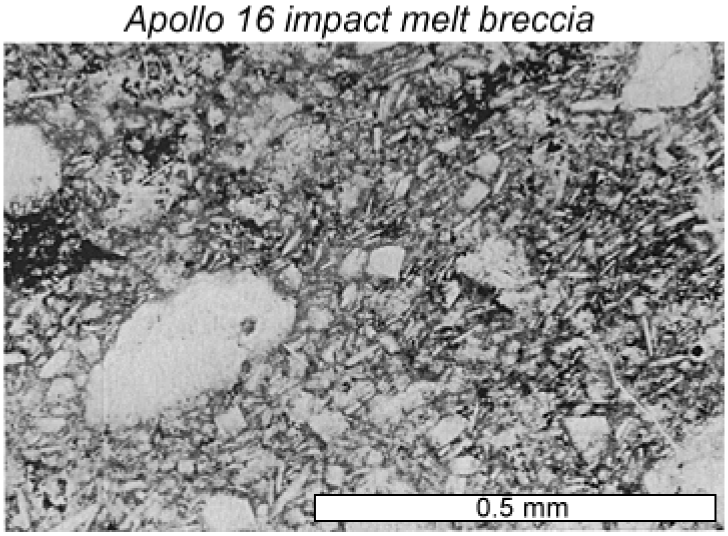


(Geologic map by Wilhelms, 1987, The Geologic History of the Moon, Plate 3, overlaid on USGS shaded relief map, courtesy of Paul Spudis.)

The dark blue area surrounding Imbrium basin on this map shows Don Wilhelms' interpretation of the extent of primary ejecta for the Imbrium basin. The Apollo 16 landing site marked with a "+" is at the edge of this geologic unit. Apollo 15 site is inside the unit and the Apollo 17 landing site is just outside the boundary. There are some uncertainties in the positions of the boundaries of the units.

Most lunar scientists do not agree with this hardnosed interpretation. They point out that many of the samples of impact melts cluster into geochemical groups that have distinctive ages. Although the ages do not vary much from cluster to cluster, they do differ beyond experimental uncertainties. Nevertheless, it is difficult to prove the Imbrium-only hypothesis wrong... and really hard to convince Randy Korotev that he should abandon the idea and embrace the cataclysm interpretation!

The skeptics do have some rock data on their side. A group of feldspar-rich impact melt breccias from the Apollo 16 landing site have ages between 4.09 and 4.14 billion years, averaging 4.12 billion years. This is substantially older than the narrow cataclysm range. If these ages represent the age of an impact, it shows that impacts certainly took place before 3.9 billion years. And if the ages represent the age of a basin, such as the Nectaris basin a few hundred kilometers to the east, then it casts great doubt on the cataclysm hypothesis. The feldspar-rich composition of these rocks is consistent with remote sensing observations of the lunar highlands surrounding Nectaris. However, the impact melted portion in the rocks consists of very small grains, implying rapid cooling. As the late Graham Ryder (Lunar and Planetary Institute) argued, this means that the embedded feldspar fragments, which come from ancient rocks, might not have been heated enough by the impact so they retain an isotopic memory of the older crustal igneous rocks. In other words, the formation of the impact melt breccia did not reset the clock to the time of the impact event.



(James, O.B., 1981, *Proc. Lunar Planet. Sci.*, 12B, p. 209-233.)

Photomicrograph of a thin slice of a feldspar-rich impact melt breccia from the Apollo 16 landing site. The small, lath-shaped grains are plagioclase, as are most of the larger, irregularly-shaped fragments. The lathy shape is indicative of crystallization from magma, in this case one formed by impact. The mineral fragments are unmelted pieces of pre-existing igneous rocks. Several small rock fragments like these have ages in the range 4.09 to 4.14 billion years, suggesting that the narrow cluster of impact melt ages required by the cataclysm hypothesis is not valid. However, the irregular-shaped mineral fragments might not have been heated enough to reset their ages when mixed with the small amount of impact melt. If so, the ages are upper limits to the age of an impact event.

Bill Hartmann (Planetary Science Institute, Tucson) has had completely different reasons for being skeptical. Driven by the lack of a sound mechanism for a cataclysm, he always preferred a declining impact rate from the time of lunar formation until 3.8 billion years ago. He suggests that this spread-out early bombardment continually pulverized the upper reaches of the lunar crust, systematically removing impact melt breccias that formed early. The only survivors as large fragments are the most recent ones, giving us the false impression that the ages of impact melts cluster between 3.85 and 3.92 billion years. He calls it the stone-wall effect.

The argument against Hartmann's interpretation is that we have samples of lava flows that have ages up to 4.25 billion years. If these surface rocks survived the declining early bombardment, surely some impact melt breccias would have, too. Ironically, if the feldspar-rich Apollo 16 impact melt breccias are shown to be over 4.1 billion years old, it would simultaneously weaken the cataclysm idea and Hartmann's stone wall hypothesis against the cataclysm interpretation!

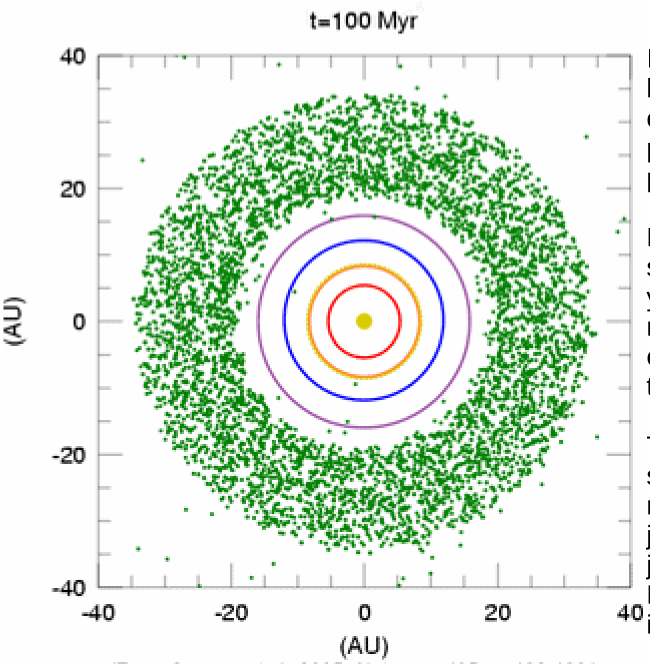
It is important to test the cataclysm hypothesis with additional lunar samples, as discussed below. For now, let's assume that there was a lunar cataclysm. What could have caused it?

Dramatic Dynamics of the Early Solar System

We normally think of the orbits of the planets as unchanging and reliable. Oh sure, stray asteroids and comets can come close to Earth and even hit it, maybe causing extinctions of numerous species. But not the planets. They stay put. We can rely on them. Well, it turns out that early in the history of the Solar System, the planets may have roamed, especially the giants Jupiter, Saturn, Uranus, and Neptune. Jupiter seems to have migrated in towards the Sun while the others wandered away from the Sun. When their orbits reached certain simple relationships to each other, serious gravitational pushing and pulling happened that violently destabilized the orbits of Uranus and Nepture, thus flinging millions of leftovers from planet formation (asteroid-to-moon-sized planetesimals) throughout the Solar System. Planets moved and craters formed, possibly in a dramatic, chaotic, messy moment of geologic history.

This is the story of the early Solar System being developed by physicists and astronomers, including Morbidelli, Tsiganis, Gomes, and Levison. Current theory says that migrating planets are a natural consequence of planet formation. Such migration would be accompanied by changes in the inclination and eccentricity of the outer planets, increasing from nice, co-planar circular orbits to those that are inclined to the ecliptic (Earth's orbital plane) and not exactly circular (they follow elliptical paths).

After the planets were constructed, Levison and his colleagues say, the Solar System still teemed with the detritus of planet formation--planetesimals that had not accreted to a planet. These stunted planets were indiscriminately hurled around by gravitational interactions with the outer planets. These interactions, called dynamical friction, caused changes in the orbits of the outer planets, too. Jupiter moved inward toward the Sun as Saturn, Neptune, and Uranus migrated outward. As Saturn drifted outward it eventually reached a resonance with Jupiter, in which it orbited the Sun once for every two orbits of Jupiter around the Sun. This is called a 1:2 resonance. This special timing of orbits of these two giant planets caused their gravitational interactions to pump up the motions of Neptune and Uranus. Tsiganis and his colleagues calculate, for example, that the orbits of Neptune and Uranus might have become highly elliptical and Neptune's orbital distance from the Sun doubled, sending it into a zone peppered with planetesimals. The planetesimals were scattered by Neptune's substantial gravity field, sending them all over the place, including into the inner Solar System to bombard the rocky planets and the Moon. The situation is so dynamic that Neptune started closer to the Sun than Uranus, but ended up farther away. See the animation below.

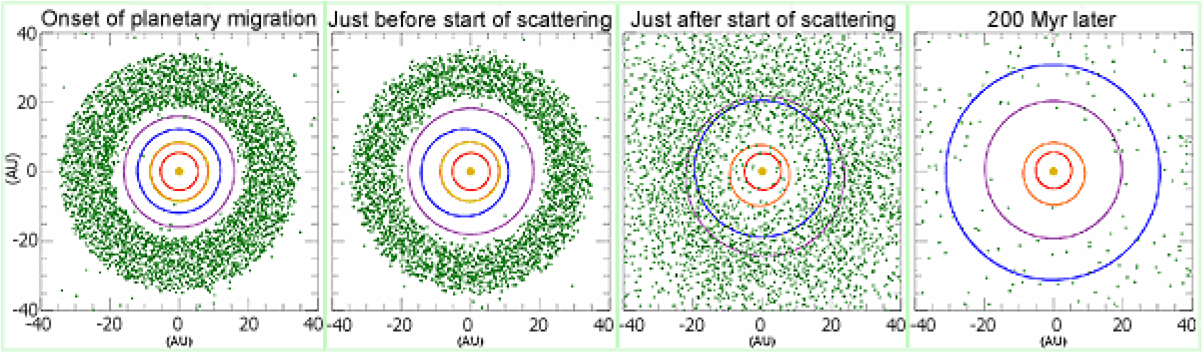


(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

In this dynamical simulation of the late heavy bombardment, the Sun is in the center, the colored circular rings represent the orbits of the four giant planets, and the green dots represent the disk of planetesimals between 15.5 AU and 34 AU.

Each panel represents the state of the planetary system at a different time, starting at t=100 million years. Saturn and Jupiter migrate slowly, reaching 2:1 resonance. This scatters Neptune and Uranus. Their extreme migrations scatter planetesimals in a short time interval--a cataclysm.

The four panels below correspond to four different snapshots taken from the simulations. From left to right: The beginning of planetary migration (100 Myr), just before the beginning of the scattering (879 Myr), just after scattering has started (882 Myr), and 200 Myr later, when only 3% of the initial mass of the disk is left and the planets have achieved their final orbits.


Onset of planetary migration

Just before start of scattering

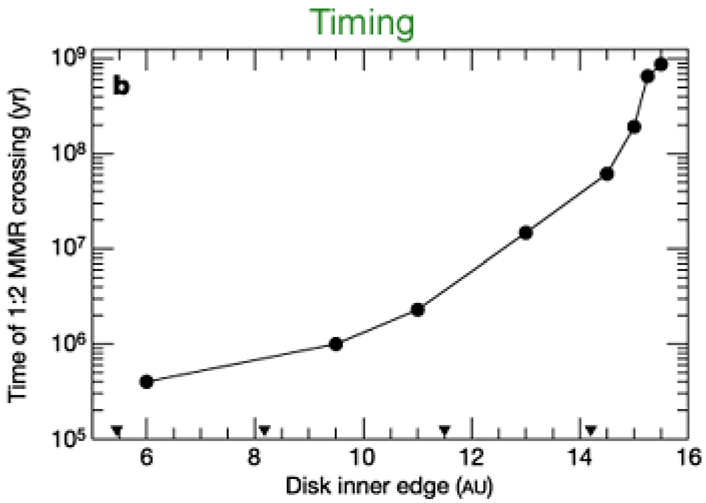
Just after start of scattering

200 Myr later

(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

There is a timing problem. The lunar cataclysm (if this is the valid interpretation of the ages of lunar impact breccias) took place between about 3.92 and 3.85 billion years ago. This means that Saturn would have to move into the 1:2 resonance with Jupiter 600 to 700 million years after the formation of the Solar System. What mechanism could delay migration of the giant planets for so long? That's the central focus of the paper by Gomes. He points out that the time at which Jupiter and Saturn reach their 1:2 resonance depends on three major factors. One, logically enough, is their distance from the resonance position. The second is the mass of materials in the planetesimal disk, particularly near its inner edge. The third factor is the relative location of the inner edge of the disk and the outermost ice giant (Neptune or Uranus).

The effect of varying the position of the inner edge of the planetesimal disk is shown in the diagram below. The farther from the Sun it is, the longer it takes for Jupiter and Saturn to reach their planet-scattering 1:2 resonance. At slightly more than 15 astronomical units (AU), the time is in the right range of a few hundred million years. By varying the other parameters, Gomes and his coworkers find that Jupiter and Saturn could have reached their 1:2 resonance between 200 million and 1.1 billion years after formation of the planets. Although not precise, it shows that the resonance mechanism is reasonable for producing the late heavy bombardment. In fact, if the lunar cataclysm is proven, perhaps its duration and age can be used to set limits on the variables that affect the timing of migration.



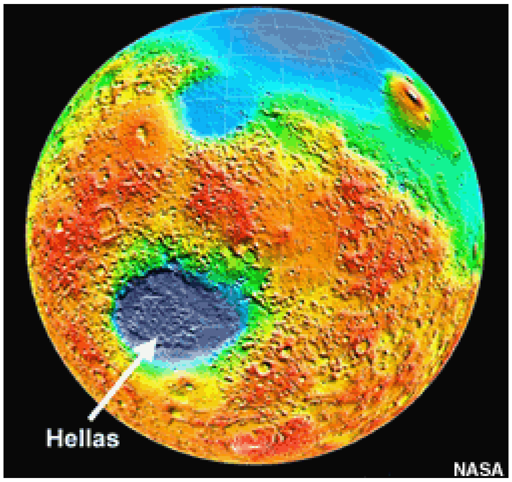
(Gomes *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

Calculations by R. Gomes and his colleagues show that the time when Jupiter and Saturn reach their 1:2 resonance depends on the distance to the inner edge of a disk of planetesimals inhabiting the outer solar system. If the inner edge of the disk lay beyond 15 astronomical units (AU), then the two giant planets reached their 1:2 resonance in several hundred million years, the right timing to have caused the lunar cataclysm.

The simulations suggest that the impactors on the Moon would be from both comets and asteroids, but the exact percentage of each is highly uncertain. However, the dynamicists are sure that there would be a lot of comet impacts, adding on the order of 8 x 10^{21} grams of cometary material to the Moon. It is curious that we do not see evidence of this influx of icy objects in lunar samples, all of which are bone dry.

Effects on Mars--Was the Early Wet Period on Mars Triggered by the Cataclysm?

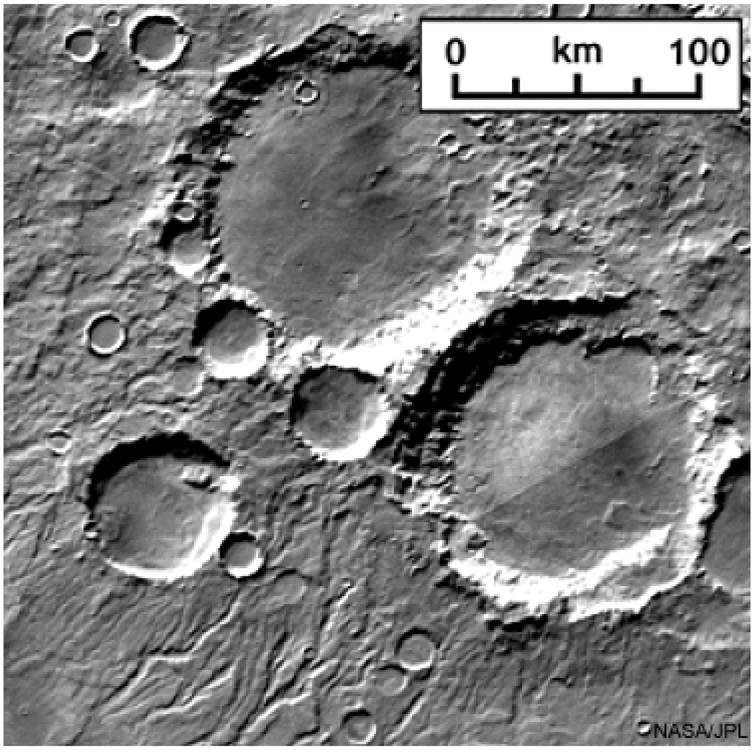
Assuming that there was a late heavy bombardment, it must have had dramatic effects on all the planets. The record is obscure on Earth, although the maximum ages for Earth rocks is about 3.8 billion years, in the right range. The late Graham Ryder (Lunar and Planetary Institute, Houston) suggested that early bombardment of the Earth provided environments in which life could arise, although some astrobiologists have suggested that the bombardment would have sterilized Earth, thus requiring life to begin multiple times. The surface of Mercury is battered like that of the Moon. (Venus has been resurfaced by volcanism, erasing all evidence for the early bombardment.) All interesting possibilities, but the effects of the late heavy bombardment may be most evident on Mars.



This topographic map of Mars shows the many craters of the martian highlands. The huge Hellas basin (~2,000 kilometers diameter) is clearly visible (blue is low and red is high elevation). It is one of many basins formed early in the history of Mars. The basins and craters dramatically record the bombardment history of the planet.

Besides forming thousands of craters larger than 20 km in diameter and perhaps a hundred basins larger than 300 km, the effects of a cataclysmic bombardment of Mars may be widespread. They could include mixing of diverse rock types, as we see in samples collected from the lunar highlands. Formation of large basins might have erased the record of an early magnetic field in Mars, now recorded only in certain regions of the highlands. Impacts would have formed large amounts of impact melt and fragmental breccias, making it difficult to find large expanses of ancient rocks.

Perhaps most interesting, a cataclysmic bombardment of Mars with icy comets would have added a substantial amount of water to the crust. It might have triggered the early, wet period in the history of Mars. Each impact might have caused rainy periods, as proposed by Teresa Sigura (University of Colorado, Boulder), leading to intense erosion of the highlands and deposition into craters that are mostly filled with sediment. Could the early, wet period on Mars have been caused by the migration of Jupiter and Saturn?



The ancient martian crust has been greatly affected by flowing water and perhaps rain. This image shows impact craters partly filled with sediment. Valley networks occur in the lower left part of the image.

Testing an Important Concept

The idea of a short, but strong, spike in the rate of impacts 3.9 billion years ago is an extremely important concept. It is not proven, as Joe Hahn (Saint Mary's University, Halifax) points out in a clear and concise summary of the dynamical calculations. He says that the good agreement with the age of lunar basin formation and the explanation for the eccentricities and inclinations of the outer planets, although very interesting, is not proof that the simulations are correct. Perhaps the eccentricities and inclinations were pumped up by the presence of other large protoplanets that eventually wound up inside a giant planet or ejected from the Solar System.

What happened to all the water in the comets that would have whacked into the Moon? How could all of it escape? If it did escape, did it also escape from Mars? More important for the Moon, did all those basins really form in a short time around 3.85 billion years ago?

Cosmochemists intend to test this idea. We can use existing Apollo samples, doing more detailed studies of those ambiguous Apollo 16 group 4 impact melt breccias and of more fragments of impact melts inside lunar meteorites. Even better, we can date samples returned by robotic missions to lunar basins. One favorite among cosmochemists is the oldest basin on the Moon, South Pole-Aitken basin. The samples could be returned on a robotic mission or by astronauts when humans return to the Moon, an event scheduled for somewhere around 2018. Settlement of the Moon, a central theme of the national Vision for Space Exploration, will enable detailed studies by astronauts living on the Moon of the ages of many lunar basins, including Nectaris and Crisium.

Future settlement of the Moon will allow for the extensive field work needed to collect the best samples to use to date lunar basins.

It is critical to test the idea of the lunar cataclysm. If proven, then the calculations done by Morbidelli, Tsiganis, Gomes, and Levison are more likely to be correct and their portrait of processes operating during planet formation may be accurate. This portrait of planetary migration explains the late heavy bombardment, the orbital parameters of the outer planets, the present orbital distribution of main-belt asteroids, and the presence of Jupiter's Trojan asteroids. If there was no cataclysm, they will have to modify their painting, perhaps drastically. As often happens in planetary science, cosmochemists and astronomers are partners trying to unravel the secrets of the early Solar System.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Cohen, B. (2001) Lunar Meteorites and the Lunar Cataclysm. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Jan01/lunarCataclysm.html
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- Vision for Space Exploration website from NASA.

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