PLANETARY SCIENCE

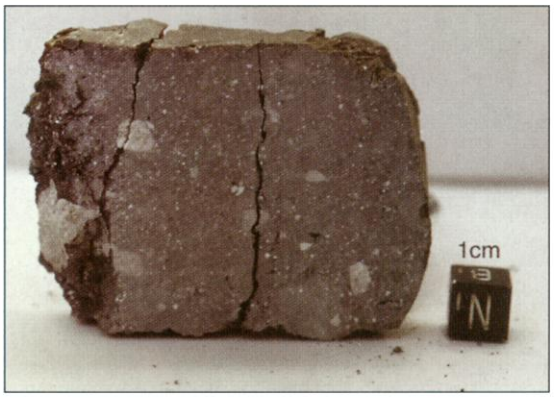
Beating Up on a Young Earth, and Possibly Life

Bits of melted rock in lunar meteorites tell of a brutal battering suffered by the moon and Earth almost 4 billion years ago, as life was getting started

Call it tough love or growing pains—Earth owes its character to the school of hard knocks. It achieved something like its present size by colliding with innumerable chunks of rock as big as cities. Then, about 4.5 billion years ago, a rogue Mars-sized body plowed into the nascent planet and splashed off enough rock to form the moon. The inner solar system quieted down considerably within a few hundred million years after that, and relative peace prevailed. But early analyses of lunar rocks returned by Apollo astronauts hinted at a sudden violent episode 600 million years after Earth's birth. Seemingly out of nowhere, a hail of objects pummeled Earth, the moon, and perhaps the entire inner solar system. Now this "late heavy bombardment" is getting strong support from analyses of rocks the astronauts never saw: meteorites that fell to Earth from the moon's back side.

Lunar meteorite analyses reported on page 1754 of this issue reveal a burst of impacts on the moon 3.9 billion years ago and nothing before that. Cosmochemists Barbara Cohen, Timothy Swindle, and David Kring of the University of Arizona, Tucson, conclude that the moon and Earth endured a storm of impacts 100 times heavier than anything immediately before or after. Such a lunar cataclysm would have scarred the moon with the great basins that now shape the man in the moon. On Earth, the same bombardment would have intervened in the evolution of life, perhaps forcing it to start all over again. "To me it seems highly likely there was a lunar catastrophe," says cosmochemist Laurence Nyquist of NASA's Johnson Space Center in Houston. But skeptics wonder how the solar system could have held off delivering such a devastating blow for more than half a billion years.

Even a pair of binoculars reveals that the moon has had a rough time of it. Analyses of impact-battered Apollo rocks suggested that violent collisions about 3.9 billion years ago—dubbed the terminal lunar cataclysm—disrupted the isotopic composition of moon rocks. Then, in the early 1990s, geochronologist Brent Dalrymple of Oregon State University in Corvallis and planetary scientist Graham Ryder of the Lunar and Planetary Institute in Houston determined precise ages of 12 bits of Apollo rock apparently melted in 12 different impacts. They found a flurry of impacts 3.9 billion years ago but none older. If the impact rate had simply tailed off from the formation of Earth and the moon about 4.5 billion years ago, as dynamical astronomers insist it must have, Dalrymple and Graham should have found impact melts as much as 4.2 billion or 4.3 billion years old. Failing that, they concluded that a burst of impacts 3.9 billion years ago had overwhelmed the few impacts that preceded it.



Lunar sample freebie. Meteorites blasted off the moon hint at an earlier cataclysm of impacts.

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The lunar cataclysm wasn't immediately accepted, however. Critics such as planetary scientist William Hartmann of the Planetary Science Institute in Tucson, Arizona, pointed out that the apparent surge might just mean that cratering was obliterating all traces of earlier impacts until it gradually slowed to the point where some could survive. And all of the dated moon rocks had come from the equatorial region of the moon's nearside, Hartmann noted, where one or two of the huge, basin-forming impacts there could dominate the record.

With the geographic constraints in mind, Cohen and her colleagues turned to the other source of moon rocks, the meteorites blasted off the moon by large impacts. Cohen chose four lunar meteorites containing bits of impact melt and dated 31 of those bits representing at least seven different impacts. None was older than 3.9 billion years. More telling, none contained the distinctive "KREEP" material (rich in potassium, rare earth elements, and phosphorus) that covers much of the nearside and tags all Apollo samples. The lunar meteorites seem to have sampled the moon far from Apollo landing sites, even on the moon's farside.

The latest results from the moon are pushing even the doubters toward a lunar cataclysm. "When we started this study," says Swindle, "I thought this would be the way to disprove it. We haven't proved there was a cataclysm at 3.9 billion years, but it passes the test." Hartmann agrees, and he now concedes that obliteration of an earlier impact record may be harder than he had thought. "The way out may be a compromise scenario," he says. "Maybe there was a fairly big spike [superimposed on the tail] 3.9 billion years ago, and we're just arguing over how big that spike was. But you would still have the serious problem of where you store this stuff for 600 million years" before dropping it on the moon.

Astronomers still don't have any good idea of the cataclysm's source. Simulations show that the gravity of Earth and the other terrestrial planets would have cleared the inner solar system of threatening debris within a few hundred million years. Collisions in the asteroid belt can shower Earth with debris, notes Brett Gladman of the Observatory of Nice, but a cataclysm would require the breakup of a body larger than 945-kilometer Ceres, the largest asteroid. The chance of that happening any time in the past 4.5 billion years is nearly nil, he notes.

As a last resort, researchers look to the outer reaches of the solar system. Dynamical astronomer Harold Levison of the Boulder, Colorado, office of the Southwest Research Institute and colleagues show in a paper to appear in *Icarus* how the newly formed Neptune and Uranus could have tossed icy debris, along with some asteroids, inward in sufficient quantities to resurface the moon, give Mars a warm and wet early atmosphere, and sterilize Earth's surface with the heat of the bombardment (*Science*, 25 June 1999, p. 2111). The only catch, says Levison, is that the two large outer planets would have had to have formed more than half a billion years later than currently thought. Levison is toying with the idea that Uranus and Neptune started out between Jupiter and Saturn, where his simulations suggest they could have orbited for hundreds of millions of years before flying out into the lingering debris beyond Saturn and triggering a late heavy bombardment. "That's my fairy tale," he says. Maybe that's just what young planetary bodies need.

–RICHARD A. KERR