A Lunar Meteorite and Maybe Some from Mars

An Antarctic find is a shoo-in as a piece of the moon, and candidates for a Martian origin have gained new respect

Houston. "Undoubtedly, this meteorite came from the moon." No one flinched. No one in the large crowd even stood to object to the provocative claim. The unanimity among petrologists, geochemists, and impact cratering specialists at the Lunar and Planetary Science Conference session* was astounding. There seemed to be no geochemical or petrological way to distinguish between the golf ball–sized meteorite picked off the Antarctic ice early last year and the rocks returned from the lunar highlands by Apollo astronauts.

The claim of a lunar origin was so well received because it had been preceded by the morning's litany of analyses made over the past few months that irrevocably link the meteorite called Allan Hills 81005 to the moon. To begin with, it had looked like a lunar breccia, a rock forged from a conglomeration of rock fragments and soil by the crushing pressure of a meteorite's impact. Its minerals were familiar from Apollo sample studies but are rare in other meteorites. Then, Toshiko Mayeda and Robert Clayton of the University of Chicago found that its oxygen isotope composition is identical to that of the moon and unlike that of most meteorites. Donald Bogard and Pratt Johnson of the Johnson Space Center reported that its soil component had been exposed to the solar wind for some time, just as soil is exposed on the moon's surface.

Analyses for 30 to 40 different elements performed by several different groups using neutron activation analysis also matched the meteorite to breccias from the bright lunar highlands. The iron-manganese ratio fit, as did the relative abundances of the rare-earth elements, the magnesium-iron ratio, the potassium-lanthanum ratio, and the amounts of other trace elements. Fifteen or so talks reporting such uniformly positive matches seemed sufficiently convincing, even a bit boring. To top it off, Allan Treiman and Michael Drake of the University of Arizona even found a dark, iron-rich chunk in the breccia that must be a bit of dark lunar mare pitched onto the highlands by an impact.

*Held 17 March at the Johnson Space Center.

Several speakers went so far as to suggest that the Allan Hills meteorite may be a more pristine sample of the lunar highlands than any rock returned by the multibillion-dollar Apollo missions. The meteorite is very low in KREEP, a chemical contaminant of all the astronaut-returned highland samples that is distinguished by enrichment in several trace elements. The huge, mare-forming impacts around the center of the near side of the moon apparently spewed KREEP from deep beneath the crust over much of the near side, including all of the Apollo landing sites. Perhaps the impact that launched the Allan Hills meteorite on its way to Earth occurred near the edge of the near side, suggested some researchers, or even on the far side. Wherever it came from, this moon rock does not seem to be just another Apollo sample.

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In the nick of time, specialists in the dynamics of impact cratering have come up with an explanation of how an impact could blast a rock off the moon. The conventional wisdom had been that an impact energetic enough to splatter debris at the escape velocity of the moon (2.5 kilometers per second) would also melt the debris or at least crush it to a powder. The lunar meteorite had not been melted or pulverized. In fact, the shock of the impact had altered the breccia fragments only mildly if at all. Jay Melosh of the University of Arizona suggested that an impact could eject mildly shocked rocks as large as tens of centimeters if they lay near the moon's surface before the impact. They would be protected there from the impact's compressive shock wave because it reflects from the surface as a tensile wave. The two waves superimpose only close to the surface, thus reducing the stress that near-surface rocks experience, while the sharp pressure surge from the impact would still provide the acceleration necessary for escape from the moon.

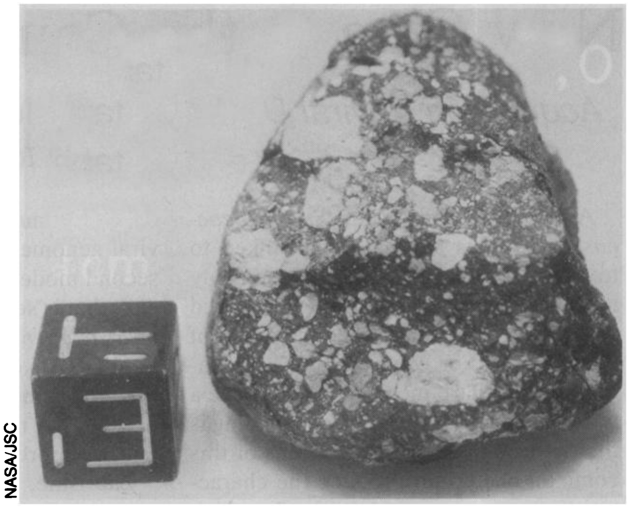
The existence of lunar meteorites having been established during the morning session, the afternoon session on possible Martian meteorites took on new significance. The psychological barrier to the idea that meteorites can originate on large bodies had been broken. There was also some impressive new evidence to consider.

Until last summer, the evidence for Martian meteorites was intriguing but far from compelling. Researchers had pointed out the striking similarities between terrestrial basalts, the dark volcanic rocks that form the ocean crust, and a group of rare meteorites that includes the shergottites, nakhlites, and chassignites (the SNC's). Their chemical and mineralogical compositions suggested that the SNC's, which have some distinctly extraterrestrial traits, originated on a body large enough to allow the kind of complex melting and crystallization that produced Earth's basalt lavas.

The catch was that the SNC's crystallized little more than a billion years ago, almost 2 billion years after Earth's moon apparently cooled to the point that volcanic activity ceased. Since less mass means both less radiogenic heating and faster cooling, even the largest asteroid, which is 1/40 as massive as the moon, would have cooled enough to shut down volcanic activity much earlier, according to this thinking. All other meteorites have crystallization ages close to 4.5 billion years, the age of the solar system.

Thus, Mars and its relatively young lava flows seemed to be the most likely source. As Benton Clark of Martin Marietta Denver Aerospace showed at the meeting, the chemical composition of Shergotty, the first of the four shergottites to be found, provides the best match to the composition of Martian soil as determined by the Viking landers. But there are other meteorites and even terrestrial samples that match nearly as well, and Shergotty may not be the most typical of the shergottites.

As intriguing as they might be, such consistency arguments never raised the idea of a Martian origin for the SNC's to a level of respectability that would



NASA/JSC

The lunar meteorite

The broken face of this meteorite, called Allan Hills 81005 for its discovery site in Antarctica, shows the white anorthosite fragments characteristic of the bright lunar highlands. Analyses of a few grams of this 31-gram rock have confirmed its lunar origin.

prompt a broad attack on the problem. But then at last summer's Meteoritical Society meeting, Bogard and Johnson presented their noble gas analyses of the Antarctic shergottite called Elephant Moraine 79001. That brought sudden respectability, if not credibility, to the suggestion of a Martian origin. By progressively heating samples to about 1200°C, Bogard and Johnson had extracted tightly held noble gases that had been trapped about 180 million years ago during the shock-induced formation of glass in the meteorite. That shock, if one accepts a Martian origin, resulted from the impact that blasted the SNC's off Mars. The trapped gases would then be part of the Martian atmosphere.

Bogard and Johnson found that the shock trapped neon, argon, krypton, and xenon in the same relative abundances as calculated for the rocks of Earth and Mars. Most other meteorites have no trapped gases, and those that do have about ten times as much xenon as the Elephant Moraine shergottite. Even more impressive, the extracted argon had a ratio of argon-40 to argon-36 as high as 1750. Corrected for the amount of argon-36 thought to have been produced by cosmic rays, the ratio climbed to 2040. Earth's atmospheric argon has a ratio of 300, and the ratio for the Martian atmosphere is somewhere between 2225 and 3500, depending on who interpreted the data.

In a late paper, Richard Becker and Robert Pepin of the University of Minnesota confirmed the uncorrected ratio of about 1800, but they based their correction on analysis of adjacent, nonglassy rock that had the same chemical composition and presumably the same exposure to cosmic rays. Their correction raised the ratio to 2400, within the range of reported Martian ratios. How an impact on an airless asteroid could trap Mars-like gases is not clear.

Becker and Pepin's measurement of the nitrogen isotopes trapped in the same meteorite was received a bit more tentatively. The ratio of extracted nitrogen-15 to nitrogen-14, even after a correction for nitrogen in the unshocked part of the meteorite, was only +130 per mil in the standard notation of isotopic ratios. The value for nitrogen in the Martian atmosphere is 620 ± 160 per mil. To test the Martian origin hypothesis, Becker and Pepin made another correction based on the assumption that there was more nitrogen in the minerals that formed the gas-containing glass than found elsewhere. They took as a measure of that excess the relative sizes of the nitrogen-argon ratios in the glass and in the Martian atmosphere. This second correction raised the value to +500 per mil, which is within the Martian range. Most listeners viewed the necessity of a second correction as regrettable but took some reassurance from the high nitrogen-argon ratio of the meteorite, which lies between that of Earth and Mars.

Although the geochemical case for Martian meteorites has become stronger and stronger, the problem of getting them off Mars remains a major obstacle. Mars's escape velocity (5 kilometers per second) is twice that of the moon. In addition, measurements of shergottite cosmic-ray exposures require that a single fragment ejected from the parent body later shattered to form the individual meteorites. The original object had to be at least 10 meters in diameter. Dynamicists can get gas, liquid, or dust off Mars easily enough, but house-size boulders are another matter—the energy required for escape seems to be always greater than the energy sufficient to destroy such large boulders.

Several dynamicists enumerated their wholly unsuccessful attempts to make Martian meteorites of the required size. Melosh's mechanism that works for the tiny lunar meteorite cannot lift anything from Mars larger than 1 to 2 meters. Ann Singer of the State University of New York at Stony Brook reported that, according to her modeling, even an assist from the 1-megabar gas pressures generated by the impact of an icy comet could not lift large particles off Mars. High-velocity gas would drag chunks larger than 100 meters off the planet, she said, except that the very pressure gradients needed for acceleration also crush such boulders to powder. Singer checked her calculations against the size of Martian crater ejecta as evidenced by the size of their secondary craters. The two sets of data seemed to be consistent. John O'Keefe and Thomas Ahrens of Caltech also failed to get 10-meter objects off Mars in their own numerical model.

However the impasse is resolved, it will be of considerable importance to planetary science. As one researcher commented in Houston, "Either we don't understand how to heat small bodies late in the history of the solar system, or we don't know how to get large rocks off large planetary bodies."

Past experience provides few indications about which side might have to give ground. Dynamicists had to back down most recently when faced with an obvious moon rock lying on the Antarctic ice. Within the past few decades, meteoriticists have had to concede that the bulk of meteorites do not come from the moon, as some of their pre-Apollo studies had suggested—the moon had melted too much. Then they had to give up on the moon as a source of the rare eucrite meteorites. These meteorites do show signs of extensive melting, which was once thought to be impossible on anything as small as an asteroid, but spectroscopists eventually found evidence of basalts on the asteroid Vesta, suggesting the melting of at least one asteroid.

Despite a certain amount of pessimism, dynamicists are anxious to test further the gas-assist mechanism as well as the effects of oblique impacts. "We do not yet know a way," says Melosh. "There is every indication that we may be overestimating the maximum size of Martian ejecta, but it may be that we just haven't been imaginative enough." Geochemists and petrologists, for their part, have a lot of work to do if they are to build a strong case for a Martian origin for all eight of the SNC's. It may be that, on closer inspection, the nakhlites and chassignites, at least, will have to be excluded as possible Martian meteorites.

—**Richard A. Kerr**