Go and Catch a Falling Star

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Although the lunar surface is largely composed of basalts and impact glasses, ground to a powdery regolith by shocks and thermal stresses, it has been recognized since the first analysis of lunar samples that the elemental abundances of this fine matrix requires a percent or two of captured meteorite material[1]. In fact, Apollo astronauts returned small chondrite meteorites from the Moon[2], including fragments welded into breccias[3], completing a remarkable cosmic voyage and raising the possibility that we might someday find Earth's protobiological materials - no longer obtainable on our repeatedly recycled planet – on the Moon, in dry storage[4]. In this issue, Yue et al.[5] predict that ~¼ of the large craters of the Moon, those impacted by the slowest asteroids, left behind significant deposits of recognizable impactor material. While controversial, this and related papers[6], coupled with ongoing reports of strange compositional anomalies on the Moon[7], have raised the stakes of lunar science yet again.

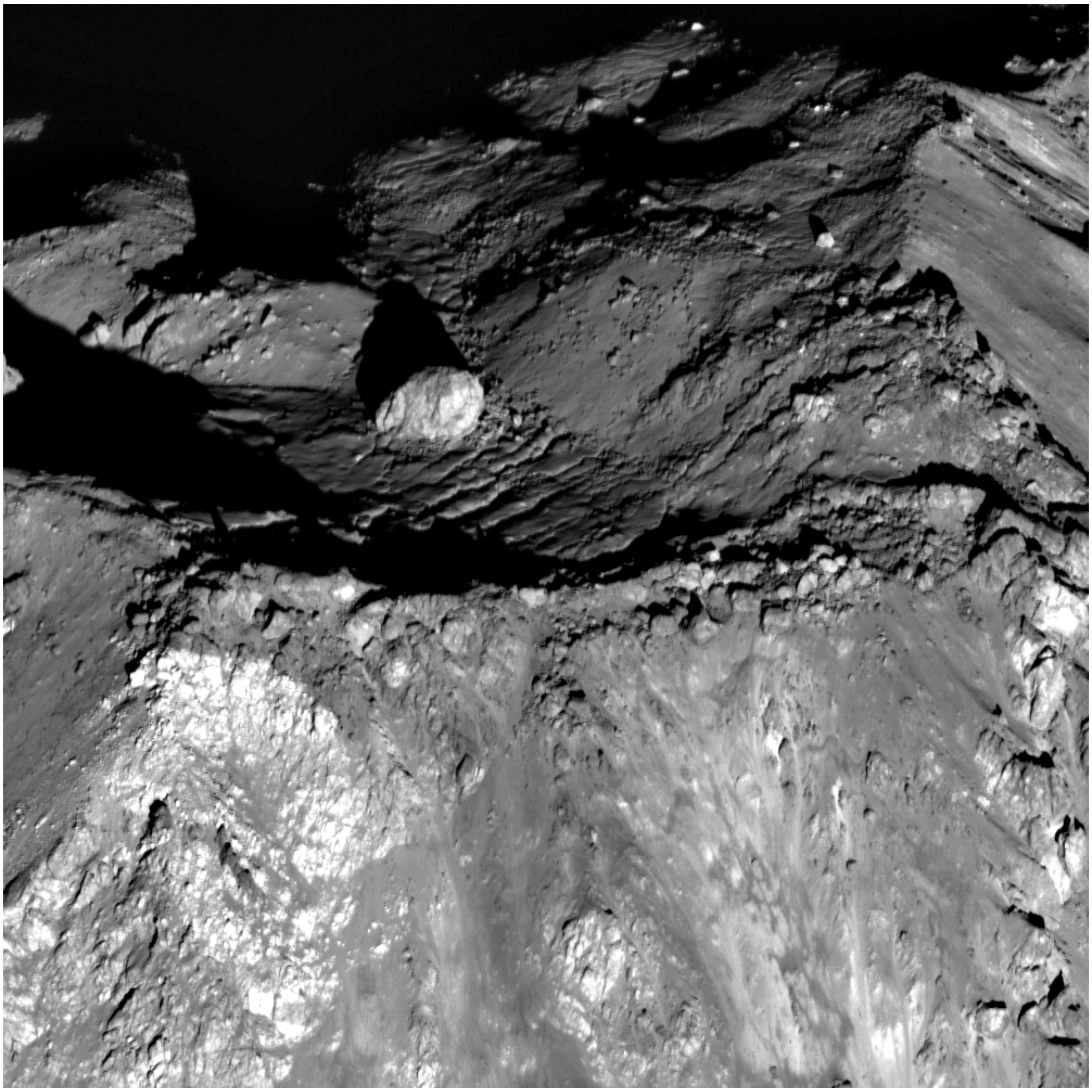
Earth's atmosphere is good at slowing down small meteors, so that fragments survive as meteorites. But asteroids larger than about 100 m plow through to the ground, colliding at ~20-25 km/s typically, and melt or vaporize, and mix thoroughly with the target rocks. Impacts into the Moon are typically far less energetic, the Moon having far less gravity than Earth, in which case capture of asteroidal bodies in recognizable form may be common[8]. Also, the Moon has been geologically inactive compared to Earth, so that much of this captured material would survive unprocessed to the present day. So asteroid survival on the Moon of itself is not a controversial idea.

The specific motivation for Yue et al. is to explain the occurrence of spinel deposits identified by India's Chandrayaan-1 mission[9], as well as olivine-rich lithologies found sporadically within Copernicus and other craters and by Japan's Kaguya orbiter[10]. Spinel, a gem-like mineral $(Mg,Fe)(Al,Cr)_2O_4$, is common on Earth and forms in deep, sequentially processed igneous rocks. It is also a common constituent of calcium-aluminum inclusions (CAIs) in chondrite meteorites and asteroids, and is also commonly found in lunar samples. Spinels are readily identified on the Moon by strong 2 μm absorptions and weak or absent 1 μm absorptions, and have now been identified in patches along the floor and central highlands of Copernicus, Theophilus and other central peaked ~100 km craters, and in patches within Moscoviense[11], a deep 400 km basin on the margin of the farside highlands, and also in extensive ~10,000 square kilometre patches in the dark basalts of Sinus Aestuum[12] near the sub-Earth point and not far from Copernicus.

According to Yue et al., asteroid-derived spinels would be concentrated within and around the central peaks of low-velocity craters by the process of crater rebound: the asteroid is splattered inside the crater, if the impact is slow enough, and then concentrates along the impact axis into recognizable units. Their proposed mechanism contrasts with the standard explanation for lunar spinels, long recognized in Apollo samples, is that repeated impact excavation has dug them out of early intrusive plutons[13]. An endogenous origin implies a very interesting early igneous history that could be consistent with the complex evolution of the lunar maria.

Impacts into the Moon by asteroids can be as slow as ~3-5 km/s, so the idea that some asteroids survive in recognizable form near or within their craters is not, perhaps, controversial. But the spinel deposits are not well correlated with central peaks, occurring in patches in and around crater peaks and floors, and in basaltic plains units. Also, the crater Copernicus, whose floor is very melt rich, would seem to require a high velocity projectile[14] perhaps inconsistent with asteroid survival within its rim explaining the spinels. One might walk the fence with an exogenic-endogenic explanation: that one or more very early splatted layers of spinel-rich asteroid material exist more widespread on the Moon, and now we are seeing the igneous and/or collisional excavations or reworkings of this buried layer (e.g. everybody is right, which means the idea is wrong).

Material from Earth can impact the Moon at less then 2 km/s, raising the possibility of finding early Earth material ejected by collisions billions of years ago. No doubt a great deal of the early Earth has ended up on the Moon, and while the delivery rate over lunar history depends on the unknown bombardment history during this primeval aeon, Earth contamination of the Moon has emerged as one of the primary selling points for a return to the Moon by human astronauts, an endeavor that is only cost effective scientifically if the science is worth tens of billions of dollars. Certainly it is, if we are to find the origin of life in the 'attic'[15]. Meanwhile, the present debate on where and how asteroids get captured by the Moon works towards developing a more quantitative understanding of the process.



Alien accumulation? Recent modeling[16] suggests that the central peaks of many of the Moon's complex craters contain substantial fractions of surviving impactor material[17]. Oblique view of the summit of Tycho's central peak (LROC NAC M162350671L,R; NASA/GSFC/Arizona State University); the large boulder is 120 metres across. Along with Copernicus, Theophilus, and other large, relatively young lunar craters, Tycho has unexpectedly rich spectroscopic diversity[18], including the identification of Mg-rich spinels. According to Yue et al. in this issue, this could be asteroid material splatted against the crater walls, and concentrated by crater rebound back to the central peak.

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