Human-Scale Lunar Surface Modification Processes

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1 Importance of Lunar Surface Studies

With the President's vision of sending NASA astronauts back to the Moon by 2020, studies of the lunar surface, such as I propose here, suddenly reemerge in importance. Increasing our knowledge of the lunar surface will both increase astronaut safety and aid in optimal landing site selection based on the scientific and engineering goals of the mission. This study addresses several key science objectives of the Science Roadmap for Solar System Exploration, which will be addressed throughout the proposal.

I will conduct several interrelated investigations of lunar surface modification processes. The lunar features under investigation are "human-scale" (a meter to a few hundred meters across), a scale which an astronaut on the lunar surface could easily perceive. Conveniently, this is also the scale of the highest resolution *Lunar Orbiter* images, which I will use in my investigations.

2 Impact Crater Ejecta Distributions

Since the end of lunar volcanism and maria emplacement 2.5 billion years ago (Head, 1976), meteorite impacts and their effects have been the dominant mechanism of modification of the lunar surface. In addition to forming craters, impacts produce solid blocks of ejecta. The fate of an ejected piece depends on its ejection velocity. Large, fast moving ejecta from large impacts will produce secondary craters, whereas smaller, slower moving ejecta will simply land on the surface. Most boulders on the Moon are impact ejecta. Investigation of such lunar surface modification processes addresses Roadmap Objective 2: *Determine how the solar system evolved to its current diverse state.*

Studies of large crater ejecta have been performed by Vickery (1986, 1987). However, large crater ejecta form secondary craters on impact, so a scaling law must be employed to determine the size of object that created the observed size secondary crater. To complement this work, I will look at smaller craters whose ejecta is still observable as boulders scattered about the crater. I will compare the small crater data with the inferred ejection velocities from Vickery (1986, 1987). This study will provide insight on the way in which impacts fracture a solid surface by comparing the size distributions of the ejecta of large and small craters. It will also elucidate the state of the preimpact surface

I have already taken data on 4 craters: three lunar craters and one martian crater. I used high resolution (1 m) *Lunar Orbiter* images taken in 1969. (To date, these are still the highest resolution images of the Moon available. The camera on the proposed *Lunar Reconnaissance Orbiter* will greatly increase the available high resolution images of the Moon.) The Mars crater was observed in a *Mars Global Surveyor* (MGS) Mars Orbiter Camera (MOC) image. I used the computer program *ImageJ* (Rasband, 1997-2005) to take my measurements. The program already had the capability to measure the diameters of the boulders. I made a small modification in the code to allow me to measure the location of each boulder in the image as well. Thus, for each of the thousands of boulders around these small craters, a few clicks gives me both the size of the boulder and its distance from the center of the crater.

Data about additional bouldery craters will be obtained. Are the differences in boulder distributions due to planetary differences, or the different crater sizes? Perhaps there are variations with terrain type. More data will give us a better feel for the natural spread in the data and for which trends are real and which are stochastic.

3 Depth and Variability of the Lunar Regolith

Of immediate importance to lunar astronauts will be the lunar regolith, the layer of broken Moon rock that blankets the surface they will walk on. The thickness of the regolith in an area is an important consideration for landing site selection. If the astronauts' mission is to find bedrock, they would want to land in an area with a thin regolith layer, whereas if they want to build underground habitats, they might want an area with thick regolith to ease the excavation process.

I will constrain the thickness of the regolith in different regions on the Moon. I will use the method of Quaide and Oberbeck (1968). They found experimentally that small craters which encounter a strength transition in the target will have particular morphologies, such as flat or mound floors, or concentric terraces. I use this method because it provides a direct correlation with a strength boundary in the target.

My preliminary measurements show that the regolith depth on the lunar farside (which has never been measured before) is about 40 meters, whereas the nearside regolith is only about 10 meters (Oberbeck and Quaide, 1967; Quaide and Oberbeck, 1968; Shoemaker et al., 1969). This preliminary result needs to be validated with further measurements. Measurements in several different regions will reveal whether the farside regolith is generally deeper than the nearside regolith, or whether a certain type of terrain, perhaps present on both nearside and farside, has deeper regolith.

Some scientists have used another method of regolith depth determination; I call it the boulder method. This method assumes that boulders around a crater indicate that the crater excavated through the regolith to a more coherent layer from which the blocks were ejected. Lack of boulders around a crater would indicate that the crater did not excavate through the regolith. Although this method sounds reasonable, I do not think it produces reliable results.

Shoemaker and Morris (1969) used this method to infer the regolith depth at the *Surveyor 7* landing site. They found that the smallest crater with a blocky rim was 9 m in diameter, and the largest smooth rim crater was 3.3 m in diameter. They assumed the craters excavated to their full depth, and thus inferred a regolith depth of 1-3 m. (Crater depth is about one-third of its diameter.) We now know that small craters only excavate to one-third their depth (Melosh, 1989); hence by the boulder method, the regolith depth would be only 0.3-1 m. This seems unreasonably thin. *Apollo* astronauts never dug down to bedrock, implying that regolith at the *Apollo* landing sites is deeper than about 3 m. Furthermore, *Surveyor 7* landed in a heavily cratered area near Tycho where the regolith might be expected to be deeper than the *Apollo* sites. Thus the boulder method in this case may underestimate the lunar regolith depth. Perhaps these very small craters merely revealed boulders present in the regolith at that location.

More recently, Wilcox et al. (2005) applied the boulder method to craters several hundred meters in diameter. However, these intermediate size craters tend to be older, and I suspect that any boulders present when the crater formed may have since eroded beyond the image resolution. Because of the many intermediate size craters with no boulders, (Wilcox et al., 2005) surmised a much deeper regolith than reported by other methods. The following section discusses how I plan to determine the validity of the boulder method for these craters by taking a fresh look at the rate of lunar surface degradation.

4 Rate of Lunar Surface Degradation

The first images of the Moon from a spacecraft, *Ranger 7*, confirmed that there is an erosive agent acting on the Moon (Gold, 1964). While some craters have sharp rims and bright ejecta blankets, others appear significantly softened, with rounder rims and colors matching the surrounding terrain. *Apollo* astronauts found partially buried boulders with the exposed parts gently rounded and the buried parts still sharp and angular (Gault et al., 1972). The Moon is clearly devoid of wind and water erosion (Hess and Calio, 1969), so the most likely source for the erosion is micrometeorite impacts.

Jaffe (1965) performed a crude experiment wherein dust or sand was sprinkled over three different crater shapes. The resulting morphologies look quite similar to many degraded lunar craters. However, on the Moon that dust must come from somewhere. A likely scenario is that the dust is produced by the constant (but small) influx of micrometeorites to the lunar surface. The micrometeorites both chip away at exposed rock surfaces and deposit material onto the lunar surface. Morris and Shoemaker (1970) examined boulders from *Surveyor* images and systematically measured their roundness. Blocks around more subdued craters were found to be twice as round as blocks around fresher craters. This rounding was attributed to solid particle bombardment and perhaps evaporation by solar wind or other high energy radiation.

Gault et al. (1972), McDonnell et al. (1972), and Morrison et al. (1972) examine lunar microcraters and their erosional effects. Gault et al. (1972) used estimates of the flux of micrometeorites in the Earth/Moon system to estimate rates of erosion. They conclude that the total amount of regolith vaporized/melted due to micrometeorite impacts is only 30 g/cm^2. Assuming a rock density of 3 g/cm^3, that number means only 10 cm of lunar material has eroded in the last 3 billion years. This number seems much too low to explain the small crater degradation I have observed in the highest resolution *Lunar Orbiter* images. Here I propose an alternative method for determining the rate of lunar degradation.

Consider this: for each of the few 100 m bouldery craters I observed, there are other craters of similar size that are highly degraded and have no boulders around them. At least two possible explanations exist: (1) The crater is older, more eroded, and the boulders it ejected have eroded beyond the limit of resolution. (2) The impact was into a deeper regolith, so the volume of bedrock excavated was lower (Wilcox et al., 2005). In the latter case, craters of equal degradation will have a varying number of boulders depending on the regolith depth, whereas in the first case, more degraded craters will consistently have fewer boulders. To distinguish between the two I need quantitative method for determining the state of crater degradation.

Analytic models for crater degradation have been proposed by Ross (1968) and Soderblom (1970), but no practical comparison to actual craters has yet been performed. To achieve this I will use photoclinometry (Beyer et al., 2003) to find the topography across small (few 100 m) lunar craters in various states of degradation. Photoclinometry is a technique which allows slope (and topography) to be determined from shading (the brightness values in an image). Photoclinometry assumes that the surface albedo is uniform across an image and that the brightness values all depend solely on the orientation of the surface with respect to the Sun. The Moon has fairly uniform albedo in the high resolution regions I will be studying. This technique has been used previously both on Mars (Beyer et al., 2003) and Europa (Hurford et al., 2005).

After topographic profiles are obtained, more pristine craters will be qualitatively identified by their sharper rims and greater depth, since degradation will soften sharp edges and cause material to slide into the bowl, filling it. In addition, the results will be compared with the profiles of Ross (1968) and Soderblom (1970). The topographic profiles across a series of progressively more degraded craters will give me a relative degradation scale with which I can compare small craters. A plot of crater degradation state vs. number of boulders (normalized to crater size) would quickly resolve the question above of why some intermediate size craters have boulders around them and not others.

5 Were Martian Gullies Formed by Liquid Water?

Surprisingly, my study of lunar surface modification also sheds light on the question of water on Mars. (Roadmap Objective 6: *Investigate the history and behavior of water and other volatiles on Mars.*) Malin and Edgett (2000) reported gullies on Mars and proposed that they were formed by liquid water in the recent past. Although the water hypothesis is currently favored, Treiman (2003, 2005) favors a dry landslide formation mechanism for the martian gullies. Considering that liquid water is not stable on the martian surface today (Ingersoll, 1971), I think it is important actively pursue reasonable alternatives. (Roadmap Objective 2: *Determine how the processes that shape planetary bodies operate and interact.*)

In *Lunar Orbiter* images I observe lunar crater rim landslides that are morphologically similar to the martian gullies, even though no lunar features formed by the action of liquid water. The Moon has no evidence for liquid water floods or valley networks (Hess and Calio, 1969), and the samples returned from the Moon are drier than Earth rocks. Hence, these lunar images suggest that the martian gullies need not have been formed by liquid water, and that morphology alone is insufficient to determine the mechanism of formation of martian gullies.

To pursue this idea, I will make a survey of high resolution lunar images to find the frequency with which these gully-like features occur. If there is enough data, I will extrapolate their global extent, and compare that extent with the extent of gullies formed on Mars. Also, I will make a detailed comparison of the morphology of the lunar features with the martian gullies. Do all types of gullies appear on both planets? Is there a specific morphology to the lunar gullies that is replicated in only some of the martian gullies? In this case perhaps some martian gullies formed like the lunar landslides while others still might indeed be liquid water formed.

Formation of martian gullies by liquid water would have important implications. Near surface water would be a valuable resource for future human explorers of Mars (Roadmap Objective 8: *Inventory and characterize martian resources of potential benefit to human exploration of Mars.*), and would reduce mission costs by decreasing the mass of water that must be shipped (Roadmap Objective 8: *Develop an understanding of Mars in support of possible future human exploration*). Also, liquid water near the surface of Mars would greatly increase the likelihood of native life. (Roadmap Objective 7: *Determine if life exists or has ever existed on*

Mars.)

6 Conclusion

The scientific objectives of this proposal are: (1) Determine impact crater ejecta distributions and assess implications for the state of the preimpact surface. (2) Place constraints on the depth and variability of the lunar regolith, comparing the near and far sides of the Moon. (3) Find relative rates of lunar surface degradation and determine whether the boulder method is a useful tool for determination of regolith depth. (4) Assess the likelihood that martian gullies formed by liquid water. Each objective addresses a part of NASA's Science Roadmap for Solar System Exploration and will provide important results for those planning the future human exploration of the Moon and Mars.

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