BRAZIL NUTS ON EROS: SIZE-SORTING OF ASTEROID REGOLITH.

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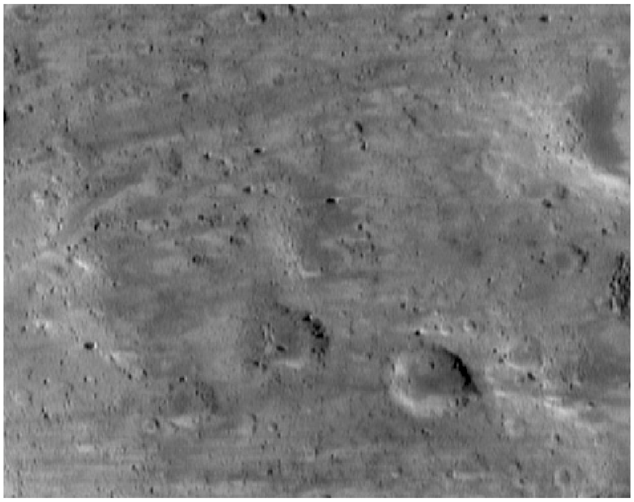
Summary: Upon repeated shaking or other periodic disturbance, granular media can undergo sorting by size. We consider the hypothesis that frequent cratering events or thermally-induced mechanical fluctuations produce size- or compositionally-sorted asteroid regolith, affecting the structure, texture, and in extreme cases the shape of asteroids. One familiar mode of grain sorting ratchets Brazil nuts to the top of a can of mixed nuts: peanuts can move into the voids displaced by large morsels, but not vice-versa. Dynamic segregation by the Brazil-nut effect is thought [1] to require a threshold shaking velocity proportional to $\sqrt{g}$; if so, size segregation may be easier to achieve on asteroids than on planets. Large blocks crowding the regolith of 433 Eros may have risen from below.

Introduction: Unlike the blocks on asteroid Ida, whose distribution appears to correlate with potential source craters and with the sweep-up faces of the rotating asteroid [2], blocks on Eros do not obey any obvious dynamical distribution. Almost certainly, a number of these blocks are ejecta fragments; however, only a handful of pits have been seen around blocks in high resolution images of Eros, arguing that most never collided at meters per second into the low-gravity regolith. Perhaps seismic resurfacing [e.g. 4] has filled the pits produced by all these landing boulders. This could be achieved by global shaking from a large impact, but the event would launch its own ejecta blocks whose pits would then have to be erased. Local cratering may have erased the pits; however, the densest block distributions occur in sparsely cratered regions. Gardening may suffice, but at nominal impact speeds this would erode the blocks themselves (which are typically quite jagged) faster than it would erode and fill the pits. The largest impacts recorded on Eros probably lofted all of the asteroid's regolith to over 100 m, but sub-orbital boulders would either land after the regolith came back, producing pits, or else have a mantled appearance, which they do not.

An alternative explanation is warranted. The concept of size sorting in asteroid regolith may have originated with a model [5] where fines draining between fault blocks result in the pitted grooves of Phobos, and with the related notion [4] that an asteroid's material may be "recycled", with regolith migrating down into fractures with every impact disturbance, perhaps conglomerating at depth, and leaving large blocks exposed to comminution and weathering. This mechanism would concentrate blocks on the surface as fines drain into asteroidal crevasses. A different explanation for coarse asteroid regolith [6] proposes the winnowing of fines by the electrostatic generation of a lossy dust "atmosphere", but this applies only to ~100 µm scales, not boulders. As rocks are comminuted to micron scales, however, one can imagine large boulders (with the smallest surface area per mass) surviving over time. Grain sorting has also been proposed [7] to explain metal-silicate fractionation in chondrite parent bodies. In terrestrial contexts, mechanical sorting has a broad history. One example [8] is the "pinstriping" of aeolean deposits, formed when small grains are preferentially scattered out of the ripple pattern by the same saltation that nudges massive grains towards each ripple edge. If small asteroids continue to prove themselves more sedimentary than igneous, such concepts might lend some insights. Here we pursue one hypothesis in particular, the dynamic sorting of asteroid regolith by impact vibrations or thermal oscillation.

Granular System Dynamics: Under mechanical excitation granular systems exhibit a wide range of behaviors. A grain bouncing on an oscillating surface may undergo chaotic or pseudo-chaotic motion depending upon the coefficient *e* of restitution [9]. If a single grain hits a group of stationary grains, many inelastic collisions occur. Depending upon *e*, the grains may either all end up moving apart, or remain stationary and in close proximity. The later is an example of one-dimensional inelastic collapse [10], and also describes a one dimensional rubble-pile.

In two and three dimensions a rich variety of behaviors are observed when a collection of grains is subject to periodic disturbance. These include convec-



tion, spontaneous piling, arching, surface waves, pattern formation, striations and segregation [11,12]. Although much of the motion is fluid-like, appropriate hydrodynamic equations are only available in the special case of highly excited dilute systems. Attempts to establish a general statistical mechanics of granular systems [13] have not developed to the stage where they are very helpful to analyzing observations.

Among the wealth of granular behaviors are two which may have direct relevance to asteroid regoliths and in the body of rubble pile asteroids:

The Brazil-Nut Effect: When a large object moves in a bed of smaller objects under the influence of gravity and vertical vibration, or other periodic oscillation, it is frequently observed that heavy large objects tend to be found at the top. Light large objects tend to be found at the bottom, an effect known as the reverse Brazil-nut effect [14,15]. Simplified models suggest that the tendency to rise or sink should depend upon both the size and the mass of the grain relative to size and mass of the background grains [16]. Two physical mechanisms have been proposed. First, a large object may be carried on a convection current until it reaches a surface from where it is difficult to re-enter the flow. Second, the vibration results in the percolation of smaller grains into the dilated regions above or below the large grain causing it to migrate. The mechanism is the subject of debate, but it is known that the Brazil nut effect may occur in the absence of convection.

One model [1] considers that small particles only displace large ones if their mean free path is equal to their diameter. This yields a relation between the threshold shake velocity v and surface gravity g, $v \sim \sqrt{g}$, beyond which segregation may occur. In other words, segregation requires less shaking for small asteroids. On the other hand, because this threshold v scales as escape velocity, an asteroid might lose regolith to space (due to a potent collision) before segregation is complete. But if 1 m/s shaking is required in Earth's gravity, for example, then only 1 mm/s is required on a typical asteroid – a typical resonance velocity for body waves following a significant cratering event [17].

If dynamical shaking has brought large blocks to the surface, estimates may be derived for how deep they originated. Suppose blocks of size r_{max} crowd the surface, having emerged from a depth z. If the unsorted size frequency distribution obeys a power law $n_o(r)=k_o r^{-\alpha}$, and the fully sorted size frequency distribution (that observed in the surface layer) obeys a power law $n(r)=kr^{-\beta}$, where sorting has continued up to a depth r_{max}, then the depth of excavation z may be estimated as $(k/k_o)r_{max}^{\alpha-\beta+1}$.

Inelastic Segregation: A collection of inelastically colliding objects will tend to aggregate. In a single component granular system, this results in the formation of regions of "granular solid'' surrounded by freely moving grains. These dense regions dissipate their internal kinetic energy and are thus long-lived.

In a granular mixture, the energy dissipated in a collision depends on the individual properties of the grains. If it is greater for like grains than for dissimilar grains, segregation would be expected to occur; within a segregated region the kinetic energy will be lower, and thus the arrangement will persist in preference to a more mixed state. This is a possible explanation for the rapid segregation and striation [18] of grains which are similar but for their density, for example. While differences in grain size and composition are certainly relevant, it is not yet clear which of these parameters (such as restitution, friction and density) most effectively determine segregation. The mysterious "fabric" of Eros [19] invites speculation, so we here entertain the notion that asteroid regoliths may be structured by this process.

Conclusion: The theory of celestial rubble piles and asteroid regoliths is young, and in a state of constant flux. So is the theory of granular media. It is therefore appropriate that the two disciplines learn and borrow from one another. Perhaps certain asteroid regoliths become striated owing to inelastic segregation; this concept and its formalism is premature. More supportable in theory, experiment and observation, is the notion that the majority of the millions of block on Eros have emerged from depth as the asteroid is jostled by impact, or (not quite equivalently) as the soil drains into asteroidal fissures, leaving the boulders behind. In extreme cases, the largest geologic units may rise to potential minima of asteroids, creating their familiar lobed appearance.

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