Triboelectrification and Razorbacks: Geophysical Patterns Produced in Dry Grains

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Electrostatic interactions between particles can dramatically affect granular flows, creating industrial safety and handling problems [K. N. Palmer, *Dust Explosions and Fires* (Chapman and Hall, London, 1973), pp. 388–389]. We present experimental data demonstrating that charging of grains can also cause spontaneous self-assembly that may generate lasting geological patterns under arid conditions. Paradoxically, we find that grains that tribocharge enough to produce small explosions, ejecting grains meters into the air, leave little net charge on grains. Rather, grains charge into strongly heterogeneous polar clusters. These assemble into stereotyped residual structures that resemble geological features, for example, razorbacks observed on Mars [“The Razorback Mystery,” July 16, 2004, http://www.jpl.nasa.gov/missions/mer/images.cfm?id=701].

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Pound for pound, common wheat flour contains nearly twice the explosive power of TNT [1]. To harness this power requires only that fine flour particles be suspended in an oxygenated cloud and exposed to a single spark. For this reason, industries expend significant efforts to control electrostatic charging in powder silos and processing plants [2,3]. Electrostatic charging of fine materials has also been put to important uses, including xerography [4], thin film manufacture [5], and air filtration [6]. Electrostatics may also play an important role in geophysical processes involving granular materials under dry conditions; for example, strong electrostatic charging has been observed during volcanic eruptions [7] as well as during aeolian transport of grains [8].

In this Letter, we hypothesize that charged granular materials will accrete into sharp peaks when driven by wind or gravity. The motivation for this proposition is straightforward: Once a small sharp peak of charged grains appears on a surface, the electric field intensity will grow dramatically in the vicinity of the peak [9]—and consequently, charged grains passing by the peak will be locally attracted or repelled, depending on their own charge distribution [10]. Since grains are known to generate enough surface charge during sandstorms to overcome their weight [8,11], we anticipate that under geological conditions a small peak can accrete charged grains—always at its sharpest points—and so will enlarge, remaining sharply pointed as it grows.

This behavior may be especially important under arid conditions, for example, on Mars, where the water content of the atmosphere is extremely low (<0.03% by weight [12]). In the Martian case, exceedingly sharp-edged “razorbacks” have been seen by NASA Mars Exploration Rovers (MERs) [13]. In Fig. 1(c), we show a razorback found by the MER Opportunity, displaying thin structures about a centimeter in height and less than a millimeter in thickness. Near these vertical formations, one can see portions of razorbacks that appear to have broken off and fallen over. These flat broken structures remain nearby the formations that they appear to have originated from, do not show rounded, eroded, edges, and are not buried by dust or sand. None of these features are consistent with razorbacks being formed over geologically significant time scales, and

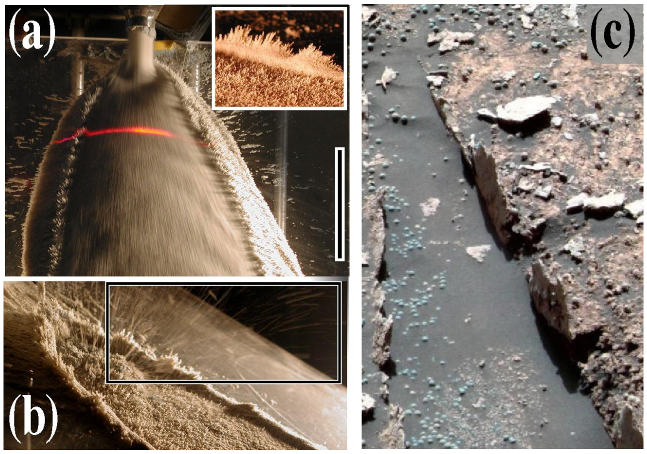

FIG. 1 (color online). “Razorbacks.” (a) Experimental flow consisting of a cascading stream of art sand (with a mean diameter of 200 ± 50 μm) bounded by razorbacks. The scale bar is about 10 cm long. The heights of the boundary structures are measured by taking snapshots illuminated by the laser sheet shown. The inclination angle of the acrylic sheet here is 28 ± 1° as measured with a digital level. The inset shows an enlargement of the bounding razorbacks after flow has stopped and the bed has fully come to rest. Each jagged tip is one grain wide. (b) Immediately after flow has stopped, the bed remains active, ejecting individual grains with high velocity (curved streaks in boxed region are individual grains). The sheet inclination in (b) is 32 ± 1°. Both (a) the razorbacks and (b) the discharging grains disappear in the presence of a static eliminator (see text). (c) Photo from the NASA rover Opportunity, obtained on sol 160 of its mission in Meridiani Planum. Photo credit: NASA/JPL/Cornell. For scale, the spherical concretions scattered throughout the snapshot are about 4 mm in diameter.

so a contemporary mechanism for their formation seems to be indicated.

The presence of razorbacks on Mars is unanticipated; the closest terrestrial analogs are associated with flowing water (e.g., speleothems [14] produced by water in caves or stromatolites [15] near hot springs), which is not consistent with Martian conditions [16]. This leads us to propose that razorbacks and other geological patterns may, in fact, be evidence of the *absence*, rather than the presence, of water. In this Letter, we confirm that formation of sharply pointed granular structures that we have hypothesized does indeed take place when grains tribocharge [10], and we draw possible parallels to Martian razorbacks.

To test our hypothesis, we perform experiments at low relative humidity (13%–20% RH) in which we release a steady stream of irregular glass grains (art sand) from a steel hopper onto an inclined acrylic sheet from a height of about 5 cm. Since the grain and the sheet materials differ, they tribocharge, and as shown in Fig. 1(a), grains spontaneously form accentuating razorbacks along the sides of the flowing stream. These formations do not appear at high RH ($> \sim 50\%$), on a metal inclined sheet, or (described below) in the presence of a static eliminator; similar results are seen using common granulated sugar in place of art sand, however. A detail of the razorback, taken about a minute after an experiment has been completed, is shown in the inset in Fig. 1(a). During and several seconds after an experiment, grains explode off of the surface with audible pops. The precise cause of these pops is not clear [8], yet the speed of these grains is substantial: The grains pepper the room, reaching heights of at least 2 meters [11]. A snapshot of the exploding grains is shown in Fig. 1(b); flying grains are evident in the boxed region.

To confirm the hypothesis that these razorbacks form by accretion of tribocharged grains onto the sharpest nearby points, we have performed tests in the presence of a commercial static eliminator (Westmont, Inc., Minerva, OH), consisting of fine carbon fibers attached to a grounded metal strip. Results of these tests, taken with the acrylic sheet inclined at 31 ± 1° and at 15 ± 2% RH, are shown in Fig. 2. In the main plot, we display the standard error of the local slope of razorbacks from images taken from the side as a function of height of the eliminator. When the static eliminator is fixed in place near the flowing surface, a smooth wake forms downstream of the flow inlet, but no sharp boundaries are created. This can be seen in the lower left inset in Fig. 2, which shows a raised wake about 15 cm downstream of the flow inlet for an eliminator fixed 25 cm above the flowing surface. As the distance from the flowing surface to the eliminator is increased, jagged razorbacks appear, and the magnitude of the local slope at the granular surface measured from snapshots increases correspondingly, as shown in the smaller plot in Fig. 2. In the upper right inset, an example is shown of the sharp and jagged razorbacks that form on top of the wake, again 15 cm downstream of the flow inlet, when the eliminator is far from the flowing surface. These experiments demonstrate that both the slope at the edges of the flow and its standard error grow significantly as the static eliminator recedes.

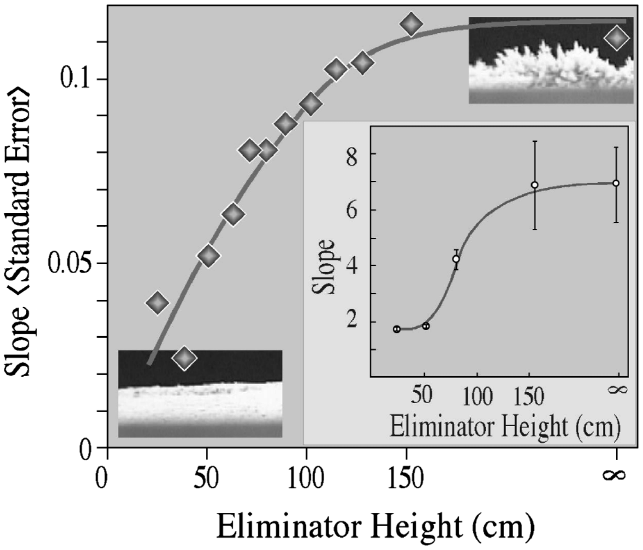

FIG. 2. Quantitative confirmation that laboratory razorbacks are produced by electrostatic influences. Main plot: Average over 3 trials of the dependence of the standard error of the local slope of razorbacks taken from side view snapshots of the flow. Smaller plot: Slopes of a laser line [cf. Fig. 1(a)] from front view snapshots of the flow. Error bars here are standard errors from many razorbacks in each snapshot and several (∼5) repetitions of the experiment at each static eliminator position.

To understand the dynamics of razorback formation, we videotaped the granular flow in the absence of a static eliminator. Two representative sequences of video frames are shown in Fig. 3. In sequence 3(a)–3(d), we see that a small cluster of grains detaches from the razorback edge [Fig. 3(a)], travels downstream [Figs. 3(b) and 3(c)], and reattaches again, elongating the razorback edge at its final location [Fig. 3(d)]. Enlargements of the snapshots [Fig. 4(a)] indicate that the traveling cluster appears to consist of about 10 grains. A second mechanism of downstream transport is shown in Figs. 3(e)–3(h). Here a monofilament cluster travels intact along the granular surface [17]. The filament remains aligned perpendicular to the inclined plane surface and flows smoothly downhill a distance of more than 10 cm. In inset (b) in Fig. 4, we show an enlargement of the filament itself alongside a sketch of the filament and its shadow in inset (c). We caution that, although filaments are ubiquitous in these charged flows, it is difficult to determine whether a particular filament may be associated with contamination, such as a stray fiber, and so we additionally searched the video record for a filament that is definitively composed of individual grains; such a sequence is shown in Figs. 3(i) and 3(j). Here we show a filament that, after traveling

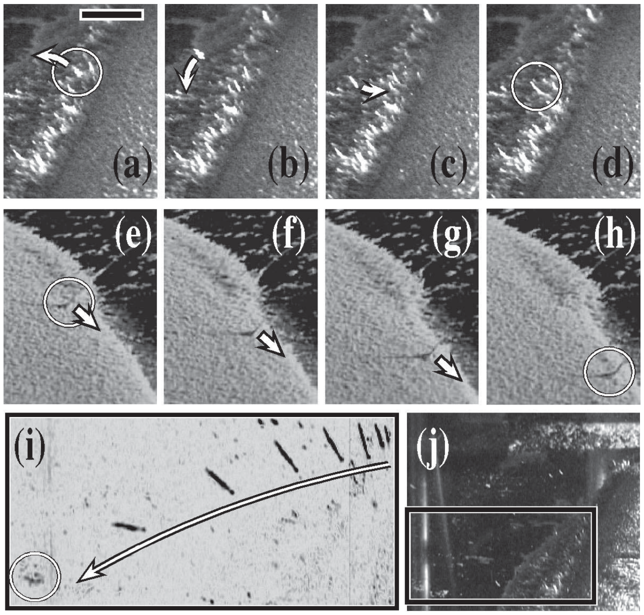

FIG. 3. Charged cluster transport [20]. (a)–(d) This sequence shows a cluster of grains, encircled, that (a) detaches from the razorback alongside the flow wake, (b)–(c) becomes airborne, and (d) reattaches further downstream to elongate the razorback at its final location. The time lapse between successive frames here is $1/30$ sec, and the scale bar in (a) is about 1 cm long. (e)–(h) This sequence shows a less common, but still frequent, transport mechanism, in which a monofilament of grains travels intact down the inclined surface. This filament travels smoothly and steadily the length of the surface (more than 10 cm). The time lapse in this case between frames is about 0.25 sec. The filament shown is very elongated and appears to consist of a stalk of single grains attached in a linear chain [see detail in Fig. 4, inset (b)]. Thicker clusters have also been seen that hop periodically downhill in a saltatory motion. (i)–(j) This sequence shows in a filament that becomes airborne and finally disintegrates (circled) into individual grains. (i) Digital differences in brightness between successive frames enlarged from boxed region in (j). Humidity in these experiments is $28 \pm 2\%$, and the acrylic sheet is inclined at $28 \pm 1°$.

along the flowing granular surface, becomes airborne and disintegrates into individual grains, as encircled in Fig. 3(i). Additionally, we remark that sequences (a)–(d) and (e)–(h) are not truly typical in that grains often fly off of the surface [cf. Fig. 1(b)] and become deposited far from their sites of origin. Nevertheless, sequences such as these do regularly occur and seem to confirm the essential mechanism that we have hypothesized.

We emphasize that it is an elementary result from electrostatics that clusters and filaments cannot be held together by a uniform charge, which would cause component particles to repel one another. Instead, charges must be strongly heterogeneously distributed. We confirm that this is, in fact, the case by measuring the net charge on grains that leave the chute at its downstream end. We do this in two ways. First, we wait until a steady state pattern is formed, then collect grains from the outlet of the chute in an insulating container, and pour the grains into a steel "Faraday cup" connected to a calibrated electrometer (Keithley Instruments Model 610CR), which provides a charge measurement. By weighing the cup (minus tare), we obtain the mean charge per unit mass on the grains. We repeat these experiments at least 3 times with the static eliminator held at each of several fixed distances from the flowing grains, and we have confirmed separately that measured charges do not change significantly if the collecting cup is located at the lateral center of the outflow or is moved spanwise to the edges of the flow. This first method of measurement could potentially introduce spurious charges during transfer of grains from the collecting cup to the Faraday cup, so in a second set of experiments, we collect all of the grains that fall from the chute in a large steel Faraday cup after the razorbacks have reached steady state, emptying and discharging the cup between each trial. Again, we reproduce the experiments at least 3 times for each of the multiple positions of the static eliminator. Results of both methods are shown in the main plot in Fig. 4.

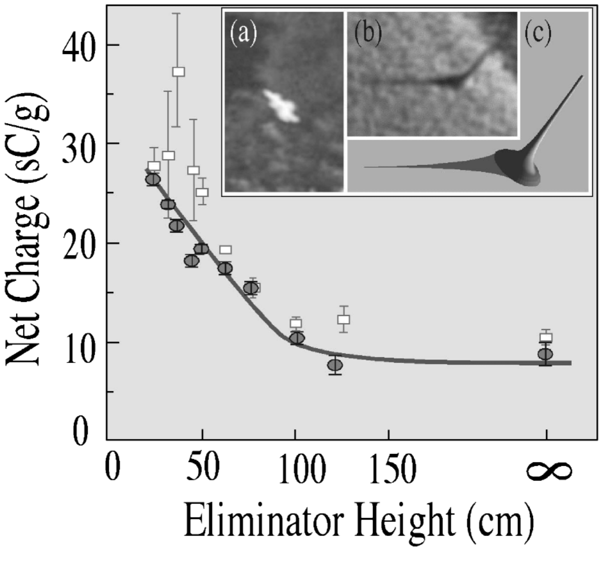

FIG. 4. Net charge of grains measured with two methods vs distance to static eliminator. Note that the net charge *grows* as the static eliminator is brought closer. Circles are data taken by receiving 4 kg from output of chute into a large Faraday cup; squares are obtained by sampling ~400 g and transferring it into a smaller Faraday cup. The thick line is to aid the eye, and error bars are standard errors over 3 replicates. Inset (a) shows an enlargement of the detached cluster from Fig. 3(b), and inset (b) shows the monofilament seen in Figs. 3(e)–3(h). The filamentary structure is very thin but is readily apparent in moving video frames [20]. To make the filament visible, in (b) we have superimposed all of Figs. 3(e)–3(h), centered at the filament, and have adjusted the brightness and contrast. We also sketch the shape of the filament and its shadow in inset (c).

From this plot, we find that the net charge per unit mass ranges up to about $\sigma_{\max} = 40$ statC/g. We can estimate the order of the electrostatic force associated with this charge by approximating grains as being spherical with radius $r = 0.01$ cm (the mean radius of our grains), of density $\rho = 2.5$ g/cc (their approximate material density), and so with charges up to $q = (4\pi/3)r^3\rho\sigma_{\max} = 4 \times 10^{-4}$ statC. Two such grains with identical charges concentrated at their centers would be mutually repelled with force $F_1 = 4 \times 10^{-4}$ dyn. This force is to be compared with the weight of a grain, which is about 10^{-2} dyn. Evidently, in our experiments (as distinct from prior sandstorm data [11]), homogeneously distributed charges generate about 2 orders of magnitude too little force to significantly perturb the inertial motions of grains.

While our flowing bed of grains and the supporting charged sheet generate higher fields collectively, this first order calculation suggests that something more than naïve considerations must be at work. Also in support of this conclusion, Fig. 4 shows that the presence of a static eliminator actually *increases* F_1; furthermore, the observed fact is that clusters of grains levitate and cling tenaciously together in the absence of a static eliminator, yet flow smoothly in its presence. These facts are all inconsistent with a hypothesis that grains in our simple experiments homogeneously charge. Rather, the experimental observations support the conclusion that grains predominantly charge heterogeneously, likely in dipolar or higher multipolar arrangements. We conclude that charge measurements, though superficially paradoxical in that net charges on grains *increase* in the presence of a static eliminator, are actually consistent with the observations that grains cluster together—which they manifestly would not do if they were identically and uniformly charged. The finding that a static eliminator increases the net charge on grains while producing smoother flow and eliminating clustered structures such as razorbacks (Fig. 2) suggests that airborne ions may be neutralizing one part of a multipole on grains, leaving the grains electrically charged. This proposition remains for future studies to validate.

In conclusion, our experiments indicate that triboelectrification can produce hitherto unforeseen patterns in industrial and geological contexts and that these patterns are consistent with the postulate that tribocharging in simple situations generates strongly heterogeneous charge distributions. In addition to razorbacks, we also observed several unexpected effects in our experiments. For example, clusters of grains hop or gyrate in complicated motions as they travel. Moreover, even within the steady granular stream, idiosyncratic patterns appear including streamwise grooves and indented circles [18]. The appearance of these phenomena provide clear evidence that there is far more that we do not know of electrostatic effects in granular systems than we do. To date, the underlying dynamics of charged granular flows has been among the least well studied or understood of granular topics, despite the fact that solids handling and processing is industrially important and may be relevant to examples of geological phenomenology, both on Earth and for planned manned missions to the Moon and Mars [19].

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[20] See EPAPS Document No. E-PRLTAO-96-034620 to download videos of these and other flows. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.