Saltation impact as a means for raising dust on Mars

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Received 8 June 2001; received in revised form 4 October 2001; accepted 19 October 2001

Abstract

Experiments were conducted under atmospheric pressures appropriate for Earth and Mars to determine the efficiency of sand in saltation as a means for raising dust into the atmosphere under wind speeds which would otherwise be too low for dust entrainment. Experiments involving intimate mixtures of sand and dust (1:1 ratio by mass) showed that after an initial flurry of activity of a few seconds duration, the bed stabilized with little movement of either sand or dust. In contrast, sands set into saltation upwind from dust beds were efficient in injecting the dust into suspension, with low-pressure Martian conditions being some five times more efficient than terrestrial conditions. This result is attributed to the higher kinetic energies of the saltating grains on Mars, which is a consequence of the higher velocities of the grains. These results suggest that sands saltating across dust beds on Mars are an effective means for setting dust into suspension. © 2002 Published by Elsevier Science Ltd.

Keywords: Mars; Mars aeolian; Mars dust; Mars wind; Mars geology

1. Introduction

Features and processes related to wind are abundant on Mars, as evidenced by sand dunes and dust storms seen in spacecraft data, including images from Mars Global Surveyor (Fig. 1) and Mars Pathfinder. These and related features attest to the frequent and widespread occurrence of winds capable of setting sand (60–2000 μm in diameter) and dust (~few microns in diameter) particles into motion.

Threshold curves relating the minimum wind speeds needed to raise particles of different sizes on Mars were derived from extrapolations to Mars from values derived for Earth (Sagan and Pollack, 1969; Hess, 1973) and from laboratory simulations of the Martian environment (Greeley et al., 1976, 1980; Iversen and White, 1982). In these curves, wind speeds are given in terms of the surface friction velocities required to set grains into motion from rest, termed static threshold (Bagnold, 1941). Friction velocities are functions of the shear stress imposed on the surface by the turbulent atmospheric boundary layer and are influenced by the roughness of the surface. Results show that the particle sizes moved by the lowest friction velocities are about 80–100 μm in diameter on both Earth and Mars, with larger and smaller sizes requiring stronger winds. Larger sizes, being more massive, require a higher velocity for entrainment, as one might expect. Smaller grains also become progressively more difficult to move, in part because cohesion and other interparticle forces become more efficient as the ratio of the surface area of the grains to their mass increases (Iversen et al., 1976). Additional considerations include boundary layer dynamics in which very small grains are immersed in a laminar sub-layer and are less effected by turbulent motions, making it more difficult for the wind to set them into motion.

The particle threshold curves for Mars (e.g., Greeley et al., 1980) are based on wind shears exerted by simple boundary layer winds blowing across relatively uniform surfaces. Although data on boundary layer winds on Mars are very limited, estimates based on Viking and Pathfinder meteorology measurements (Hess et al., 1977; Schofield et al., 1997; Magalhaes et al., 1999) and predictions from global circulation models (GCMs; Haberle et al., 1999) suggest that winds of sufficient strength to exceed those needed to entrain the fine dust (~few microns in diameter; Pollack et al., 1977, 1979; Smith et al., 1997) are rather infrequent. Nonetheless, the numerous dust storms observed on Mars, both locally (Briggs et al., 1977) and globally (reviewed by Kahn et al., 1992; Zurek et al., 1992), show that dust is raised from the surface.

The apparent discrepancy between the curves for particle threshold and the observed dust in the atmosphere led

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to considerations of mechanisms for raising dust other than simple boundary layer wind-shear. For example, dust devils have long been suspected to be an effective means to achieve dust threshold on Mars (Ryan and Lucich, 1983). Active dust devils have been observed from orbit (Thomas and Gierasch, 1985; Edgett and Malin, 2000), along with inferred dust devil “tracks”. Active dust devils were also detected from Mars Pathfinder lander data (Metzger et al., 1998; Smith and Lemmon, 1998). In addition to dust devil processes, surface roughness at the sub-meter scale and atmospheric stability influence both particle threshold (White et al., 1997) and flux (Greeley et al., 2000), in some cases resulting in higher surface shear stresses driven by lower overall wind speeds.

Bagnold (1941) demonstrated that the impact of grains in saltation could set particles into motion in a process he termed dynamic threshold. In this mechanism, sand-size grains (the size most easily entrained) are set into saltation and as they return to the surface in the saltation trajectory, they “splash” into the bed, dislodging other grains. As reviewed by Pye and Tsoar (1990), more recent observations in wind tunnels (Willett and Rice, 1989) and computer simulations (Anderson, 1987) show that this might be an effective means for particle threshold under wind regimes which otherwise are insufficient to entrain particles. This concept was extrapolated to Mars by Peterfreund (1985).

In order to gain insight into the mechanism by which saltation impact might raise dust into suspension on Mars, exploratory experiments were carried out under terrestrial and Martian atmospheric conditions. This report describes the results from these experiments and the implications for Mars.

2. Experiments

Two types of experiments were conducted. In the first case, particles of two different sizes were mixed together, one consisting of dust-size particles and the other consisting of sand-size particles. The wind speed was set just above saltation threshold for the sand and the results were observed. In the second case, a bed of sand was placed “upwind” from a bed of dust. Wind tunnel speeds were then set at friction velocities 1.2 times higher than the threshold for sand, but were below speeds required to entrain the dust. The sand was then saltated across the bed of dust and the results were photographed and monitored visually. In some cases, high-speed motion pictures were also obtained to enable analysis of particle movements and to observe the interactions of the sand with the dust bed in “slow motion”.

Experiments were run in wind tunnels at Arizona State University (ASU) and at NASA-Ames Research Center (ARC; Fig. 2). Both are open-circuit, atmospheric boundary layer wind tunnels suitable for simulating aeolian processes (see appendix in Greeley and Iversen, 1985). The ASU tunnel is 18 m long and has a $1 \times 1 \times 2$ m cross section. It operates at one atmosphere pressure (1 bar) at speeds as high as 40 m/s. The Mars Surface Wind Tunnel (MARSWIT) at NASA-ARC is capable of operating at atmospheric pressures from 1 bar to as low as 3.5 mbar and at speeds as high as 100 m/s at low pressure. Although MARSWIT can be run with carbon dioxide, previous experiments demonstrated that running “Earth” air at $\sim 10$ mbar pressure and in ambient laboratory temperatures produces the same fluid density as carbon dioxide at 6.5 mbar, appropriate for Mars. We define this as the nominal Mars case for runs in MARSWIT.

The test sections of both wind tunnels are constructed of 2.5 cm thick Plexiglas to allow viewing and filming the experiments. Boundary layer wind profiles have been obtained for a wide range of atmospheric pressures, freestream wind speeds, and surface roughness configurations from previous experiments (White et al., 1979). These enabled friction velocities to be obtained for the experiments conducted in the investigations of saltation impact.

The movement of particles was detected visibly through the sides of the test section either directly for 1 bar runs or indirectly using a high-resolution video system for the low-pressure runs in which the chamber was evacuated.
Particle movement was also detected instrumentally with an electrometer probe placed at the exit end of the wind tunnel and with a laser interferometer. As soon as particles were set into motion, they impacted the electrometer probe and implanted a triboelectric charge, which was registered on a meter. The particles also interrupted a beam of laser light across the test bed, which registered as a decrease in signal on a detector on the opposite side of the test bed. The signals from both instruments were monitored and recorded.

3. Results

3.1. Mixed particle size

In the beds of mixed particle sizes, the dust-size grains consisted of Xerox toner, which was about 8 µm in diameter and had a density of about 1.0 g/cm³. This material was used because it is in the size range of dust on Mars (Smith et al., 1997) and its density enables scaling to the Martian gravity in regard to lift from the surface in the experiments. The sand-size grains consisted of silica microspheres, which were 100 µm in diameter and had a density of 2.4–3 g/cm³. Both sets of particles were thoroughly mixed in a ratio of 1:1 (by mass) and placed as a uniform bed 2 m long by 0.5 m wide and 0.01 m thick in the test section of MARSWIT. Several experiments were run under both Earth (1 bar) and Martian (10 mbar) atmospheric conditions. In all cases, the wind friction velocity was set a few percent above threshold for the sand-size grains.

Observations showed that the sand-sized microspheres were set into saltation, as one would expect, at a wind speed slightly above threshold. After a few seconds, the sand-size grains on and near the surface of the bed were removed, leaving only the dust-size grains, and particle movement ceased. This stage was easily visible because of the change in contrast from gray (mixed particles) to dark (Xerox toner dust), as the light-colored microspheres (sand) were deflated by the wind.

A slight increase in wind speed above that in the initial stage of the experiments resulted in the movement of a few more microspheres, but the surface again reached a stable condition. Repeating this procedure eventually removed all of the exposed or partly exposed microspheres, leaving a “lag” deposit of the dust. The maximum freestream wind speed attainable in MARSWIT (40 m/s at 1 bar) was not sufficient to entrain the dust.

Although some of the dust which was deposited on the microspheres became entrained as the microspheres began movement (as evidenced by dark deposits of Xerox toner on the electrometer probe), the process of dust entrainment from a bed of mixed particles was found to be inefficient as a means for raising dust. Rather, the observations showed that a lag deposit of dust quickly stabilized the bed, even when subjected to very high wind speeds.

3.2. Saltation impact on beds of dust

This series of experiments involved beds of sand-size grains placed upwind from beds of dust. Free stream wind speeds were set 20% higher than those required for the threshold for sand saltation, depending upon the size and composition of the particles. The saltating grains then impacted the dust beds. These experiments were conducted in MARSWIT under both Earth and Mars conditions and at ASU under 1 bar atmospheric pressure.

A variety of materials was used in these experiments. Sands used as the saltation “triggers” included two sets of quartz particles, one with an average diameter of 200 µm and the second with an average diameter of 500 µm. Under Martian atmospheric conditions, these particles had threshold friction velocities of 2.0 and 3.0 m/s, respectively, under Martian atmospheric conditions. For these experiments, beds of sand 0.05 m thick were placed about 1.5 m upwind from the dust beds. The dust consisted of fragments of basaltic rock which had been crushed and sieved to an average diameter of 16.6 µm. The dust particles had a density of 2.83 g/cm³ and a threshold friction velocity of 5.5 m/s under Martian atmospheric conditions. Experiments were also conducted using fly ash (14.8 µm in diameter; a by product from coal-fired power plants) and silicic pumice (13.5 µm in diameter). There were no differences between the fly ash and the pumice observed in the experiments.

The masses of the sand and the dust were measured before and after each test to determine how much dust was entrained as a function of the mass of sand in saltation. It was found that 0.15–0.7 g of dust is removed per gram of sand. Tests were conducted over a range of atmospheric pressures from Martian and Earth conditions. As shown in Fig. 3, there is a trend suggesting that the process might be more efficient on Mars under low atmospheric pressures than on Earth.

Six runs were conducted during which high-speed motion pictures were obtained. Two of the runs were conducted under low atmospheric pressure conditions. Two cameras were mounted to view the test bed, one from an overhead perspective and one from the side of the tunnel to view the saltation cloud in cross section. The filming rate was 1000 frames/s (fps; the “normal” film speed for motion pictures is 16 fps). In most of the runs, this rate was too low to capture as much detail as was sought; moreover, the wind speeds were so high that the flux was too great to enable clear separation of most of the individual grains in saltation (the scene tended to be “swamped” with particles). We also found that the side views were of limited use because the depth of field (the focus range) is very short with most of the image area being out of focus. Despite these limitations, the film records provided insight into the interaction between the saltating grains and the dust beds.

Three modes of interaction were identified in the motion pictures. In the first mode, many grains “splashed” into the
dust, forming small craters and dislodging the dust which was dispersed into the boundary layer as a spray of particles, most of which formed a diffuse cloud and passed into suspension. However, some of the dust returned to the surface. The craters which resulted from the impact of the sand grains continued to deform after the grains passed out of view.

In the second mode of interaction, as the sand grains impacted the dust bed, some of the dust was dislodged as clumps or sheets which either disaggregated into clouds of dust, or were transported by the wind along the surface, passing out of the field of view. Observations during the experiments showed clumps of dust rolling along the floor of the tunnel and the formation of the clumps is likely to have been initiated in this mode.

In the third mode of interaction, sand grains were seen to bounce off the bed of dust, leaving no imprint, or to gouge a groove in the dust bed but without dislodging any of the fine particles; some grains also plunged into the dust bed, remaining buried and not entraining any dust into the air.

4. Summary and conclusions

Saltation impact is known to inject particles into the wind under conditions which might otherwise be inadequate for threshold. Termin dynamic threshold by Bagnold (1941), this process occurs on Earth and was inferred to occur on Mars. Preliminary experiments (Fig. 3) show a trend in which a greater mass of dust is set into motion as a function of impacting sand mass with progressively lower atmospheric pressure, reaching a factor of about five times greater dust mass injected for Mars in comparison with Earth.

The greater efficiency of raising dust by saltation impact under Martian conditions is attributed to the higher overall windspeeds required for saltation in the low-density atmosphere. Previous studies have shown that static threshold for optimum-sized grains (about 80–100 µm in diameter, or fine sand, for both Earth and Mars) is 5–10 times greater on Mars than on Earth (Greeley et al., 1980). In turn, this leads to particle velocities which are some three times greater on Mars (Greeley et al., 1983). As a consequence, impacting grains at the end of their saltation trajectory would impart more kinetic energy to the surface and have the potential for injecting more dust into the atmosphere.

Analyses of high-speed motion pictures shows that saltating sand grains under both Mars and Earth atmospheric pressures interact with dust beds in one of the three modes: (1) creating an impact crater from which dust is ejected, (2) gouging the dust bed and causing clumps or sheets of dust to be dislodged (some which break apart and set dust into suspension), or (3) indenting the dust bed surface or becoming buried in the dust but without dislodging any dust.

In conclusion, saltation impact appear to be a viable mechanism for injecting dust into suspension on Mars when sands are upwind from dust beds. They do not appear to be very effective when sand is intimately mixed with dust.
Acknowledgements

I appreciate the thoughtful reviews provided by D. Busche and F. Costard which enabled clarification of parts of the manuscript. I also thank Rod Leach, Garrett Kramer and Gary Beardmore for assistance in running the wind tunnels at NASA-Ames Research Center and Arizona State University, Dan Ball for filming some of the runs, Sue Selkirk for graphics support, and Stephanie Holaday for manuscript preparation. The support by G. Joseph Hartman and members of the Thermo-Physics Facilities Branch, NASA Ames Research Center, is gratefully acknowledged. This work was supported by the NASA Planetary Geology and Geophysics Program.

References


Smith, P.H., Lemmon, M.T., 1998. Dust properties at the Pathfinder site. EOS 79 ((F-549)).


