Conditions for aeolian transport in the Solar System

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Sand dunes, which arise wherever loose sediment is mobilized by winds that exceed threshold speed and grains are sufficiently strong to survive collisions, are ubiquitous in the Solar System. However, current threshold theories usually neglect physical processes that become relevant under exotic conditions and are in disagreement when extrapolated to extraterrestrial planetary bodies. Here we draw on results in contact, rarefied gas, statistical and adhesion mechanics to present a theory for the fluid and impact thresholds of aeolian transport that encompasses the various conditions present in Solar System bodies. Our theoretical predictions are consistent with available experimental threshold observations and indicate that these thresholds strongly depend on local environmental conditions everywhere but Earth. Our results suggest, among other things, that Titan’s dunes are locally sourced and that Mars’s high threshold makes its dunes more resistant to motion. This work highlights the role of dunes in understanding atmospheric dynamics and surface sediment. Further studies are needed to include hitherto neglected and still poorly understood processes.

We have developed theories to find the two threshold friction velocities $u$ that must be exceeded by wind to move sand and form dunes: the ‘fluid’ threshold, the wind required to move a particle from rest; and the ‘impact’ threshold, the minimum wind to maintain steady saltation. Mass transport scales in excess of the latter, whereas saltation must start from the former. This is done from first principles, and by employing more stringent or recent results from aeronautics and contact mechanics that are not typically considered in aeolian studies (Methods). Each theory has a single physically meaningful free parameter, which is found by fitting to a newly compiled comprehensive data set. Using these theories, we provide revised predictions of the thresholds across the Solar System where dunes are known to exist (Fig. 1a–f), paying special attention to the range of environmental conditions on each planetary body.

The fluid threshold of motion is defined by a balance between the forces retaining a grain that is resting in a pocket on a bed of grains, and the forces that can remove it from this pocket. Weight and adhesion forces correspond to the former, while drag and buoyancy to the latter. The lift force can act to retain or remove the grain, depending on shear and fluid properties (Fig. 1h). These forces all have functional forms constrained from theory, apart from the lift force, where we employ refined empirical predictions for the respective coefficients. The complete torque balance in a fragment of pocket geometry reads $r_c F_c + r_s F_s = m r_c F_c + m r_s F_s$, where the moments and forces are defined graphically in Fig. 1g. Expanding and non-dimensionalizing this equation (Methods), we can write the fluid threshold of motion as the sum of two fractions that are equal to unity,

$$1 = \frac{\alpha}{\Theta_p} + \frac{\beta}{\Phi_p},$$

where $\alpha$ and $\beta$ depend on geometry and the drag and lift coefficients, and $\Theta_p$ and $\Phi_p$ depend on fluid and solid properties. The Shields-like number $\Theta_p \propto \alpha / d$ non-dimensionalizes the fluid speed at the particle centre, whereas $\Phi_p$ is non-dimensionalized in $\Phi_p \propto d$ by the adhesion due to grain-surface energy. The crossover between these limiting behaviours, where winds must overcome adhesion or weight, respectively, depends on all parameters. As an example, for typical quartz grains on Earth this transition occurs for a grain size of roughly 40 $\mu$m, hence, dune sands are little affected by adhesion, while dust grains are strongly affected. This may not, however, be the case on other planets.

There is one unaccounted-for constant required to close the solution for the fluid threshold: the ratio of the characteristic length-scale between particles in contact, $d_0$, and roughness at the contact scale (Fig. 1). Assumption that this ratio, $\beta$, is approximately universal for natural sand grains, we determine it to be $\beta = 7.84$ by fitting the theory to wind-tunnel and field measurements of the fluid threshold (Methods). This allows prediction of the fluid threshold on each planetary body of interest, if the dimensionless parameters $\alpha$, $\beta$, $\Theta_p$, and $\Phi_p$ are known. Our formulation builds on previous hydrodynamic approaches (Supplementary Section 1), with the following improvements: it accounts for the lift and adhesion forces explicitly, improves the parameterizations for the lift and drag coefficients, and has just one free parameter that is specific to sediment transport.

Using well established theory on the behaviour of gases (Methods), observations of temperature and pressure, and measured material constants (Supplementary Table 1), we find that the predicted fluid entrainment threshold spans three orders of magnitude for reasonable grain diameters across the Solar System (Fig. 2a). To first order, this range is controlled by fluid kinematic viscosity (Extended Data Fig. 1). We see that both particle composition, and variability in pressure and temperature, can lead to a wide range of threshold wind speeds on a given planetary body—with the exception of Earth, where these parameters vary little. These predictions are mostly higher than alternative theories, while being similarly accurate when compared with experimental data (Extended Data Figs. 2 and 3). The sensitivity of drag pressure to wind stress—that is, the drag coefficient, $C_D$—varies greatly across these environments, depending on

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lost during a collision to the granular bed and viscous dissipation, and momentum gained by fluid drag and lift during the hop\textsuperscript{1}.

The effective restitution coefficient includes contributions from particle elasticity, granular friction and viscous dissipation\textsuperscript{16,18,20}. It may be back-calculated from experimental and field studies of the impact threshold, by solving for trajectories at the conditions where the threshold was measured (Supplementary Section 2). We seek an intuitive and parsimonious parameterization for $e$. Drawing on studies showing that $e$ depends on a competition between particle inertia and viscous dissipation\textsuperscript{16,20}, we assume that other contributions vary little among materials. To test this idea we examine the relation between $e_0$, the restitution coefficient associated with a fixed common impact angle of $\sim 10^\circ$, and the Galileo number, $G = \sqrt{(\rho_s/\rho - 1)g\mu^2/v}$ ($\rho_s$ is the solid density, $\rho$ is the fluid density and $v$ is the kinematic viscosity), which has been identified as an important parameter governing sediment transport\textsuperscript{21} (Fig. 3d and Extended Data Fig. 4). The resulting correlation is strong; we suggest a heuristic logistic functional form for $e_0(G)$, where the only free parameter $e_0(G = 10^5) = 1/2$ defines the crossover from the end-member cases of a fully damped and fully elastic impact event (Methods). By fitting to observations we find $\nu_c \approx 1.65$ (Fig. 3c,d), which can be implemented in a forward model to predict the impact threshold. This theory builds on previous contributions\textsuperscript{16}; the main improvements are that forces are represented more accurately, and that the number of free parameters is reduced because the ejection speed of grains does not need to be prescribed.

The computed impact thresholds cover a span in magnitude that is comparable to the fluid thresholds, with the latter exceeding the former in nearly all cases—probably leading to hysteresis in sediment transport events\textsuperscript{3} (Fig. 3a and Supplementary Fig. 2b). Compared with previous theories\textsuperscript{5–7} our approach is more accurate when compared with observations, and predicts lower impact thresholds in less dense fluids (Extended Data Figs. 5 and 6). Our formulation of the impact threshold becomes ill defined for small grain sizes (Extended Data Fig. 8 and Methods). This occurs approximately where the two thresholds reach parity, and where turbulent fluctuations—neglected in our Reynolds-averaged description—are expected to become important in determining grain trajectories. While alternative methods avoid this pathology by imposing that the impact threshold smoothly approaches the fluid one in this limit\textsuperscript{21}, there is a distinct lack of data to test ideas about small grains.

Our theory permits us to resolve characteristic saltator trajectories, and therefore the impact speed (Extended Data Figs. 7 and 9). This characterizes the energy that results in wind-driven sediment attrition, a critical mechanism in wearing down particles and potentially producing dust\textsuperscript{21–25}. By employing a canonical model for yield during particle impact\textsuperscript{16}, using the material properties of sediments (Methods), we inspect the ratio of the impact speed at threshold over the speed required to cause yield, $v_i/v_Y$ (Fig. 3b). This constitutes an attrition parameter; if this ratio is very small, relatively strong sediment particles were probably produced from weathering rather than attrition of bedrock, whereas large values would indicate weak particles that could not survive impact and make dunes. To build intuition regarding the meaning of numerical values for $v_i/v_Y$, we compute them for two representative materials on Earth—quartz and gypsum. While the former is stronger than the latter, both form competent sand grains that range—rather than shatter—when transported by wind\textsuperscript{24,25}. Gypsum, however, exhibits substantial attrition over just a few kilometres of transport, while quartz requires an order of magnitude larger distance; their corresponding values for $v_i/v_Y$ differ by roughly 50%. Turning to other planetary bodies, we see striking variability in the attrition susceptibility of candidate dune sands. The slope of the attrition parameter with grain size does not have a consistent sign across environments. More negative slopes may imply efficient production of dust, if there is equal transport susceptibility of grain sizes\textsuperscript{25}.

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**Fig. 1 | Dunes and the forces that create them.** a–f, Aeolian features on Earth (a), Mars (b), Titan (c), Venus (d), Pluto (e) and Triton (f). The forces (F) and moments (v) of lift (L), buoyancy (B), drag (D), gravity (G) and adhesion (A) around the pivot (magenta dot) for the fluid threshold of the yellow particle. h, Graphical definitions of fluid velocity ($\omega$), elevation ($\omega$), particle diameter ($d$) and fluid velocity at the particle centre elevation ($\omega_c$), with a close-up of the blue inset in g showing the mean free path of gas molecules ($\lambda$). i, Close-up of the pink inset in g of a particle contact and microscopic roughness characterized by $B$. Credits: a, NASA (National Aeronautics and Space Administration)/Goddard Space Flight Center/Ministry of Economy, Trade and Industry of Japan/Earth Remote Sensing Data Analysis Center/Japan Resources Observation System and Space Utilization Organization, and US-Japan Advanced Spaceborne Thermal Emission and Reflection Radiometer Science Team; b, NASA/Jet Propulsion Laboratory (JPL)-Caltech/Arizona State University; c, NASA/JPL-Caltech/Italian Space Agency; d, NASA/JPL; e, NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute; f, NASA/JPL. More information on the images in a–f is provided in Supplementary Table 2; scale bars are 10 km.

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on how rarefied and fast the fluid is\textsuperscript{11} (Fig. 2b,c,f). This broad swath in fluid properties is mostly captured by pressure-controlled experiments, with the exception of small bodies that maintain very thin atmospheres such as Triton. There is a distinct lack of experimental data where adhesion dominates the fluid threshold, and where the threshold is extremely high (Fig. 2c,d).

Once wind exceeds the fluid threshold, saltation is initiated. At this point the mechanism for threshold changes qualitatively: the dominant way in which grains leave the bed is by ejection due to impact from colliding grains\textsuperscript{1}. The forces used in the fluid threshold above, apart from adhesion, also describe the physics of saltating grain trajectories (Methods). Interestingly, there are two almost universal characteristics of these trajectories: saltators eject from the bed at an approximately fixed angle; and typically only one saltator is ejected per impact, while other grains ‘splash’ short distances and quickly deposit\textsuperscript{18,19}. If we couple trajectory dynamics with a model for the speed ratio between the impacting ($v_i$) and ejecting ($v_e$) saltators—that is, the effective restitution coefficient $e$—we can find the minimum friction velocity necessary to maintain a steady state, $v_i = e v_e$ (Fig. 3e). This state corresponds to a balance between the momentum
Fig. 2 | Fluid threshold prediction and observations. a, Predicted fluid threshold friction velocities for grains of different candidate and known sediments, on each planetary body (legend for the latter in b). b, Fluid regime cast in Knudsen ($K$) and Mach ($M$) number space for predictions (bands) and observations (stars) at the fluid threshold; the background greyscale gradient indicates $C_D$. Bands in a and b show the range based on known temperature and pressure variability. c, Histogram comparing observed fluid thresholds and their predicted values; a 1:1 line (cyan) is overlaid. d, Equation (1) (cyan) overlaid on a histogram of observations. e, f, Schematics of the continuum and free-molecular limits corresponding to the $K$ values above them, respectively.

Fig. 3 | Impact threshold prediction and observations. a, Predicted impact threshold friction velocities for grains of different candidate and known sediments on each planetary body. Legends follow those of Fig. 2. b, Predicted attrition of characteristic particles at the impact threshold. Bands in a and b show the ranges for each planet based on known temperature and pressure variability. c, Histogram comparing observed impact thresholds and their predicted values; a 1:1 line (cyan) is overlaid. d, Heuristic $e_0(G)$ (cyan) overlaid on a histogram of observations; the dashed line (cyan) defines the fit parameter $C$. e, Trajectory at the impact threshold for 100 $\mu$m basalt on Venus (grains, path and vectors are consistently scaled).
We have highlighted how large variations in atmospheric conditions and particle properties on each planetary body lead to markedly different aeolian sediment transport thresholds by employing better representation of the mechanisms that change substantially outside Earth. Indeed, the minimal effect of environmental and sediment variability on Earth’s thresholds is a red herring; these play major roles in all other bodies we study (Fig. 2a). Of course, there are mechanisms known to play a role in the saltation threshold that we have not represented here: notably, capillary and electrostatic forces. Our analysis, however, has revealed that there are potentially important and previously unconsidered mechanisms that we do not currently understand—such as lift at low pressure (Supplementary Section 3) and the fluid threshold in the adhesion limit (Fig. 2d). We do not explicitly account for adhesion effects in the impact threshold theory; some results indicate that adhesion may be neglected for saltation.

This work may help to resolve some unsettled debates in planetary aeolian geomorphology. For Pluto, our analysis supports the hypothesis that methane ice constitutes the dunes west of Sputnik Planitia, but finds that present-day winds may be insufficient to activate dunes. The dark streaks on Triton are probably inactive after plume deposition, due to high entrainment thresholds and erosion susceptibility. Venusian sands are probably sourced by non-aeolian mechanisms, and transport has negligible hysteresis, akin to water that is 100-μm much faster than on Earth (Fig. 3b), and require stronger winds to move.

Substituting the forces and moments into the torque balance, we can write the equation of motion in a line between the contacts of the two bed particles downwind of the threshold particle. The forces, moments and torque balance read:

\[ F_x = \frac{\pi}{2} d e^{-\beta}, \quad \frac{F_D}{\pi} = 1 / \sqrt{\gamma}, \]
\[ F_L = \frac{G}{2} d + d^2 d^1, \quad \frac{F_I}{\pi} = 1 / \sqrt{\gamma}, \]
\[ F_B = \frac{k_g p d^3}, \quad \frac{F_c}{\pi} = 1 / \sqrt{\gamma}, \]

where \( B \) is the ratio of contact-scale roughness to the interparticle distance in contact, \( C_L \) is the lift coefficient and \( A \) is the ratio of a sphere’s frontal area to natural sediment effective frontal area with respect to the flow for drag and lift.

Equation (1) is greater than unity, the state is below the fluid threshold. Ideally \( \gamma \) is measured, typically in the correct geometry and environment with an atomic force microscope. Without this ability, we employ the Lifshitz theory to estimate the Hamaker constant, \( A \) (ref. 1). For two perfect like spheres, \( A \) and \( \gamma \) are coupled such that

\[ \gamma = A \frac{12 \epsilon e^2}{N}, \quad (5) \]

where \( \epsilon = 0.165 \text{ nm} \) (ref. 1). Lifshitz theory takes information about the solids in contact and the gas in which they are immersed, and provides an approximation for \( A \) such that

\[ A = \frac{3}{4} k_B T \left( \frac{N - n}{n} \right)^2 + \frac{3h \nu_{c} \left( \frac{n - n_{c}}{n} \right)^2}{16 \sqrt{2} \left( \frac{n}{n_{c}} + \frac{n_{c}}{n} \right)^3}, \quad (6) \]

where subscripts \( s \) and \( f \) denote solid and fluid, respectively, \( k_B \) is Boltzmann’s constant, \( T \) is the temperature, \( \epsilon \) is the static relative permittivity, \( h \) is the reduced Planck constant, \( \nu_{c} \) is the frequency of the absorption peak (assumed to be \( 3 \times 10^{14} \text{ s}^{-1} \) for all media) and \( n \) is the refractive index. \( n \) depends on temperature (and pressure for the gas), so over the relatively small variations we consider on each planetary body we assume a linear relationship of \( n \) constrained by known values of \( n(T, p) \). This calculation is performed for all cases apart from tholin, where \( \gamma \) was measured with an atomic force microscope by Yu et al. While it is clear that \( \gamma \) depends on the environment from the equation above, in lieu of alternatives we assume to first order that the atomic force microscopy measurement for tholin holds in all cases. In Supplementary Table 3 we provide referenced values for the material-specific constants used in this calculation for all other cases.

Fluid threshold fit. We compiled previously measured fluid threshold friction velocities from experiments and field studies to find the unknown parameter \( B \) (refs. 3,9,10). This parameter is the ratio of the length-scale of surficial particle roughness and the interparticle distance across which adhesion forces act and therefore finding it through regression onto experimental data from natural particles implicitly encodes the role of surficial roughness on natural sediment into the theory, which assumes that the grains are spherical. We chose to only include measurements where the humidity was reported to be less than 15%, to minimize the effect of capillary forces. To implement this fit, all the other parameters that make up equation (1) must be known for each observation. We used the variables stated in each paper where possible. Otherwise, we assumed that measurements were taken at \( T = 20^\circ \text{C} \) and standard pressure for the elevation at which they were measured, then made use of the equations in Fluid property theory if required. Not all papers report \( \gamma \) for their experiments; in lieu of this important parameter, we used reference Hamaker constants from measurements in other literature for each sediment material (UK, NL, AUS) (or a similar material if a measurement could not be found: that is, clover seed was assumed to adhere the same as walnut shells). These data are collated in Supplementary Data 1.

In the main text and result we only fit using one parameter, \( B \); there is however an additional free parameter, \( A \), that in principle should depend on the sediment shape. In an ideal configuration \( A = 1 \), and when allowing it to vary freely alongside \( B \) to match observations we find it to be \( A = 1.01 \). Given the similarity between these results, and the negligible effect on accuracy between them (Extended Data Fig. 2a,b), we fix \( A = 1 \). The fitting parameters are found by minimizing

\[ \sum_{i=1}^{N} \left( \frac{U_{e,\text{observed}} - U_{e,\text{predicted}}}{U_{e,\text{observed}} + 1} \right)^2, \quad (7) \]

with \( N = 567 \) being the number of fluid threshold measurements compiled in this study. This form of the loss function was used to ensure that there is no bias toward the magnitude of \( u_{e} \).

Fluid property theory. We assume that the gases can be described as ideal, with the kinetic theory of gases, and with respect to viscosity using a Lennard-Jones pair
potential between molecules. This allows us to find the fluid properties related to sediment transport using just temperature, pressure and material constants. The dynamic viscosity ($\mu = \rho v$) is found using the Lennard-Jones model:

$$T_e = \frac{T_h}{\varepsilon},$$

where $A_v = 1.0614, \beta_0 = 0.14874, C_0 = 0.52487, D_0 = 0.77320, E_v = 2.6178$ and $G_v = 2.43787$ are fit parameters for the reduced viscosity collision integral $\Omega_{1,2}^2$ (ref. 1). The Boltzmann constant is $1.38 \times 10^{-23}$ K$^{-1}$. Material constants $\sigma$, $\varepsilon$ and $M$ are given in Supplementary Table 3. This formulation is used, instead of the Sutherland formula employed in other sediment transport studies, because it extrapolates more reliably, since it does not assume hard-sphere repulsion at short range.

Fluid density is found using the ideal gas law$^{2}$.

$$\rho_l = \frac{\rho MT}{RT},$$

where $\rho = 8.314 \text{J K}^{-1} \text{mol}^{-1}$ is the gas constant.

The mean free path is found using the kinetic theory of gases$^{13,27}$, where

$$\lambda = \frac{\lambda}{p} \sqrt{\frac{\pi R T}{2 M}}$$

The Mach ($\mathcal{M} = c/\lambda_0$), Knudsen ($\mathcal{K} = \lambda/d$) and Reynolds ($\mathcal{R} = u_d d/\nu$) numbers are related by

$$\mathcal{K} = \mathcal{M} \sqrt{\frac{\mathcal{R} \mathcal{E}_T}{2}}. $$

Grain trajectory theory. Grains in flight obey an equation of motion defined by the force balance,

$$m_p \frac{\partial v}{\partial t} = F_{D} + F_{L} + F_{K} + F_{B},$$

where $m_p$ is the particle mass, $v$ is the particle velocity and $t$ is time. Substituting the forces in Fluid theory and rearranging, we find the following equation of motion (written in the complex plane for simplicity):

$$\frac{\partial \psi}{\partial t} = \frac{C_0 + i C}{4} \left[ \Psi_{p}(\psi) - \Psi_{i}(\psi - v) \right] s/d - i \left( 1 - \frac{1}{2} \right) g,$$

where $\psi = \psi + i \gamma$ is the particle velocity vector, $u_\psi = u_\psi(z) + i \dot{z}$ is the horizontal fluid speed at the particle centre, $\gamma$ is the elevation (where zero is defined as the base of a particle at rest on the bed) and $g$ is the acceleration due to gravity. This equation states that particles have drag, lift and effective weight altering their path as they are in flight. The drag and lift magnitudes depend on the square of the relative speed of the particle with respect to the flow, as to their angles, while gravity acts constantly and always downward. Implicit in this formulation is that the particles do not extract momentum from the flow, since the formulation of gravity acts constantly and always downward. Implicit in this formulation is that the relative speed of the particle with respect to the flow, as to their angles, while we employ is only affected by the roughness that grains impart to the flow$^{2}$.

Grain trajectory theory. The restitution parameterization. To find a restitution coefficient parameterization, we compiled previously measured impact threshold friction velocities from experiments and field studies$^{4-9,13-18,90-99}$. As noted in the main text, this choice of parameterization requires a single fit parameter, $C$. To find $C$, all the other parameters that make up the trajectory equation of motion (Grain trajectory theory) must be known for each observation. As for the fluid threshold measurements, we used the variables stated in the paper where possible. Otherwise, we assumed that measurements were taken at $T = 20 \degree C$ and standard pressure for the elevation at which they were measured, then made use of the equations in Fluid property theory if required. These data are collated in Supplementary Data 2. With these known, we calculate $\nu/v$, and $\psi$ for each measurement using the observed $u_c$; our theory for $\psi$ should ideally be equal to $v/\nu$ for each measurement.

We also compiled data from other studies where the restitution coefficient of particles hitting a loose bed was explicitly measured$^{10-18,90-99}$. If these measurements were from studies where wind was blowing particles, we only considered the measurements at the impact threshold. This distinction is important since the bulk restitution will be altered by particles extracting momentum from the flow and bed particles not being at rest. As above, we used the variables stated in the paper where possible. Otherwise, we assumed that measurements were taken at $T = 20 \degree C$ and standard pressure for the elevation at which they were measured, then made use of the equations in Fluid property theory if required. These data are collated in Supplementary Data 3. It is clear from one of these studies$^{40}$ that a good approximation for the effect of impact angle on restitution—also employed elsewhere—$^{40}$

$$\frac{\epsilon}{\epsilon_{0}} = \frac{1 - c_{0} \sin(\theta_{i})}{1 - \epsilon_{0} \sin(10)}$$

where $\epsilon_{0} = 0.828$ is found experimentally$^{40}$. We choose $10 \degree$ arbitrarily, but require that all restitution coefficients are normalized as if they are found from equal impact angles when trying to derive a parameterization.

Relevant studies indicate that the restitution coefficient of saltators is independent of impact speed$^{4-9,13-18,90-99}$. This contrasts with the restitution coefficient of a single particle impacting a plane, which increases with impact speed after a threshold and is predictive using the Stokes number$^{4-9,13-18,90-99}$. For the narrowly defined restitution coefficient we attempt to accurately model, we are interested in non-unique saltators in the limit of vanishing sediment flux during events where a loose bed also produces splash. In this case, we seek a non-dimensional parameter that does not include a velocity scale, and clearly relates to the restitution coefficient from experiments. Guided by the trend for both explicit and implicit data (Extended Data Fig. 4c), we suggest to first order that

$$\epsilon_{0} = \frac{\mathcal{G}}{10^{16}} + \mathcal{G},$$

where $\mathcal{G}$ is the distillation of multiple mechanisms that produce bulk restitution of the saltating particle, and includes the role of shape variability in natural sediment grains$^{4-9,13-18,90-99}$ through regression onto the experiments where they are employed. We find $\mathcal{G} \approx 1.65$ using a least-square regression onto the data described above. This approach assumes imperfectly that the restitution coefficient could potentially reach unreasonably high values (such that saltation would sustain without fluid flow, that is $\epsilon > 1$) if both $\mathcal{G}$ and $\theta_{i}$ are large. In lieu of a more appropriate data-informed alternative, however, we use the accurate formulation above, noting that our predictions lie well outside these unreasonable regimes. This formulation is consistent with intuition (as described in the main text) and data where available$^{40}$ (Extended Data Fig. 4).

Yield speed theory. We assume that the yield speed ($\nu_{y}$) for two like spheres is modelled by

$$\nu_{y} = \sqrt{\frac{26Y}{E_{y}}} \mathcal{P}_{s},$$

where $Y$ is the yield stress, $E = E(1 - V)$ is the effective elastic modulus ($E$) and $V$ is the Poisson ratio (upper case here to avoid confusion with the particle speed used
elsewhere in this manuscript). This formulation is based on the Von Mises criterion that solids yield when the maximum pressure exerted at the contact exceeds 1.6Y. The yield stress is not necessarily related to the elastic modulus in the same way for all materials; in lieu of yield stress data for all materials used in this study, however, for geologically relevant materials the following three semiempirical relationships are relatively accurate:

\[
\psi = 0.19 + 1.6 \log_{10} \left( \frac{\gamma}{\tan(\beta_y)} \right), \quad H = 2 \times 10^{-2} E^{0.3}, \quad \frac{\psi}{E} = \frac{T_D - \gamma}{T_D - T_m},
\]

(20)

from ref. \(^1\), ref. \(^2\) and ref. \(^3\), respectively, where \(H\) is the hardness measured with a nanoindentor of angle \(\beta_y\), \(E(T_m)\) is the elastic modulus measured at temperature \(T_m\) and \(T_D\) is the melting temperature. We note that it would be ideal to use a theory on chipping of geologic materials over this approach, but current theories require measurements of fracture toughness that have not been taken for material and environments applicable to this study\(^4\). In the special case of ‘tholin (light)’, we crudely assume that the yield stress \((\gamma_{tholin})\) is related to the yield stress of ‘tholin (dense)’ \((\gamma_{tholin})\) by the ratio of their densities, such that \(\gamma_{tholin}/\gamma_{tholin} = \rho_{tholin}/\rho_{tholin}\), since the yield stress should decrease with aggregate density and experimental evidence is not available. We treat this yield speed as a characteristic value of attrition, instead of a robust predictor.

Data availability
All data are available in the Supplementary Data files. Source data are provided with this paper.

Code availability
The code used to produce this paper can be accessed at https://doi.org/10.5281/zenodo.6480898.

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Extended Data Fig. 1 | Wind profiles. (a) Mean horizontal wind speed with elevation for a fixed friction velocity ($u_\ast = 0.3$ m/s) and grain size ($d = 100\mu$m) for the six bodies of interest using the empirical relation in Supplementary Information Text S4. The grain center is denoted with a black line. (b) Dimensionless presentation of (a), where $u_\ast^+ = u/u_\ast$ and $z^+ = zu_\ast/u$. 

Extended Data Fig. 2 | Fluid threshold prediction comparison to data. Four methods for predicting the fluid threshold are compared to observed data, where the vertical axis is $u_{\text{observed}}/u_{\text{predicted}} - 1$ (for the labelled prediction) and the horizontal axis is the Galileo number, $G$. References for the observations are given on the right, where markers with shaded interiors signify experiments not using standard Earth conditions. The correlation coefficient ($r^2$) for each log-log comparison of $u_{\text{observed}}$ versus $u_{\text{predicted}}$ (that is Fig. 2c) is annotated. (a) The prediction in the main text, where $A = 1$. (b) The prediction except $A$ is a free-parameter. (c) The prediction using the empirical relation of Iversen & White (1982). (d) The prediction using the semiempirical theory of Shao & Lu (2001).
Extended Data Fig. 3 | Fluid threshold prediction comparison to each other. The relative error between the alternative predictions of Shao & Lu (2000) (S&L) and Iversen & White (1982) (I&W) with the prediction in the main text for the fluid threshold for average conditions on each body. Each sediment candidate is given for (a) Earth, (b) Mars, (c) Titan, (d) Venus, (e) Pluto and (f) Triton.
Extended Data Fig. 4 | Restitution mechanics and empirical fit. References for the observations are given on the bottom right, where markers with shaded interiors signify experiments not using standard Earth conditions or field data, markers with solid interiors signify explicit measurements of the restitution coefficients outside wind tunnels. Magenta and yellow markers are from studies where the restitution coefficient is measured or noted, values for the vertical-axes of markers with other colors are inferred from simulated trajectories. All horizontal-axes are the Galileo number $G$. (a) The ratio of the ejection to impact velocity of a characteristic saltating grain, that is the restitution coefficient $e$. (b) The angle the grain impacts the bed, with the theoretical fixed ejection angle denoted (cyan line). (c) The restitution coefficient normalized such that it impacted the bed at a fixed angle ($\theta_\downarrow = -10^\circ$), $e_\downarrow$, with the empirical relationship used in the main text relating the two axes (cyan line) (Methods).
Extended Data Fig. 5 | Impact threshold prediction comparison to data. Four methods for predicting the impact threshold are compared to observed data, where the vertical axis is $u_{\text{observed}}/u_{\text{predicted}} - 1$ (for the labelled prediction) and the horizontal axis is the Galileo number, $G$. References for the observations are given on the right, where markers with shaded interiors signify experiments not using standard Earth conditions or field data. The correlation coefficient ($r^2$) for each log-log comparison of $u_{\text{observed}}$ versus $u_{\text{predicted}}$ (that is Fig. 3c) is annotated. (a) The prediction in the main text. (b) The prediction using the semiempirical theory of Kok (2010) (note: the vertical axis bounds are extended in the inset to show the full data extent). (c) The prediction using the semiempirical theory of Pähtz & Durán (2018). (d) The prediction using the semiempirical theory of Claudin & Andreotti (2006).
Extended Data Fig. 6 | Impact threshold prediction comparison to each other. The relative error between the alternative predictions of Kok (2010) (K), Pähtz & Durán (2018) (P&D) and Claudin & Andreotti (2006) (C&A) with the prediction in the main text for the impact threshold for average conditions on each body. Each sediment candidate is given for (a) Earth, (b) Mars, (c) Titan, (d) Venus, (e) Pluto and (f) Triton.
Extended Data Fig. 7 | Trajectory analysis example. (a-c) Each point on the lines with color corresponding to the colorbar on the left are for a trajectory of a 1 mm quartz grain at average Earth conditions leaving the bed with an ejection velocity of $v_\parallel$ from the horizontal axis. The solid black line denotes the impact threshold friction velocity, while the black dot and the corresponding dashed black lines denote the unique pair of the friction velocity and ejection velocity at the impact threshold. (a) The ratio of the ejection to impact speeds for a trajectory. (b) The impact angle for a trajectory, with the cyan line indicating the ejection angle. (c) The ratio of the ejection to impact speeds for a trajectory, normalized as if the impact angle was fixed ($\theta_\downarrow = -10^\circ$), $e_\parallel$ (Methods). The green line (also in (d)) is the ‘target’ restitution coefficient for this case using the empirical relation found in Extended Data Figure 4c. (d) The minima for each line in (c) plotted against the friction velocity. We define the impact threshold as the intersection of the trend and the green line.
Extended Data Fig. 8 | Contrasting trajectory examples. Trajectories like Extended Data Figure 7c for Basalt grains at average Mars conditions of size (a) $d=1\,\text{mm}$ and (b) $d=10\,\mu\text{m}$. The green lines are the ‘target’ restitution coefficient for each case using the empirical relation found in Extended Data Figure 4c. The qualitatively different behavior in the neighborhood of the solution shows how this formulation of the impact threshold loses meaning for small grains. The minima for each successive curve of fixed friction velocity in (a) are close and transition smoothly, and $u_\ast$ and $v_\uparrow$ are not extremely different. This is in contrast with (b), where the minima close to the target restitution rapidly diverges as $u_\ast$ changes, and $v_\uparrow$ is extremely small at the minima relative to $u_\ast$. 

![Graphs showing trajectory examples](image-url)
Extended Data Fig. 9 | Trajectory diagnostics. Predictions for the characteristic saltator trajectory at the impact threshold with varying grain diameter for (a) impact speed, (b) impact angle, (c) hop height and (d) hop duration. Bands show the range for different candidate and known sediments on each planetary body (see legends in (c) and (d)) based on known temperature and pressure variability.