How does sand move on Mars?
Possible solutions to some long-standing mysteries

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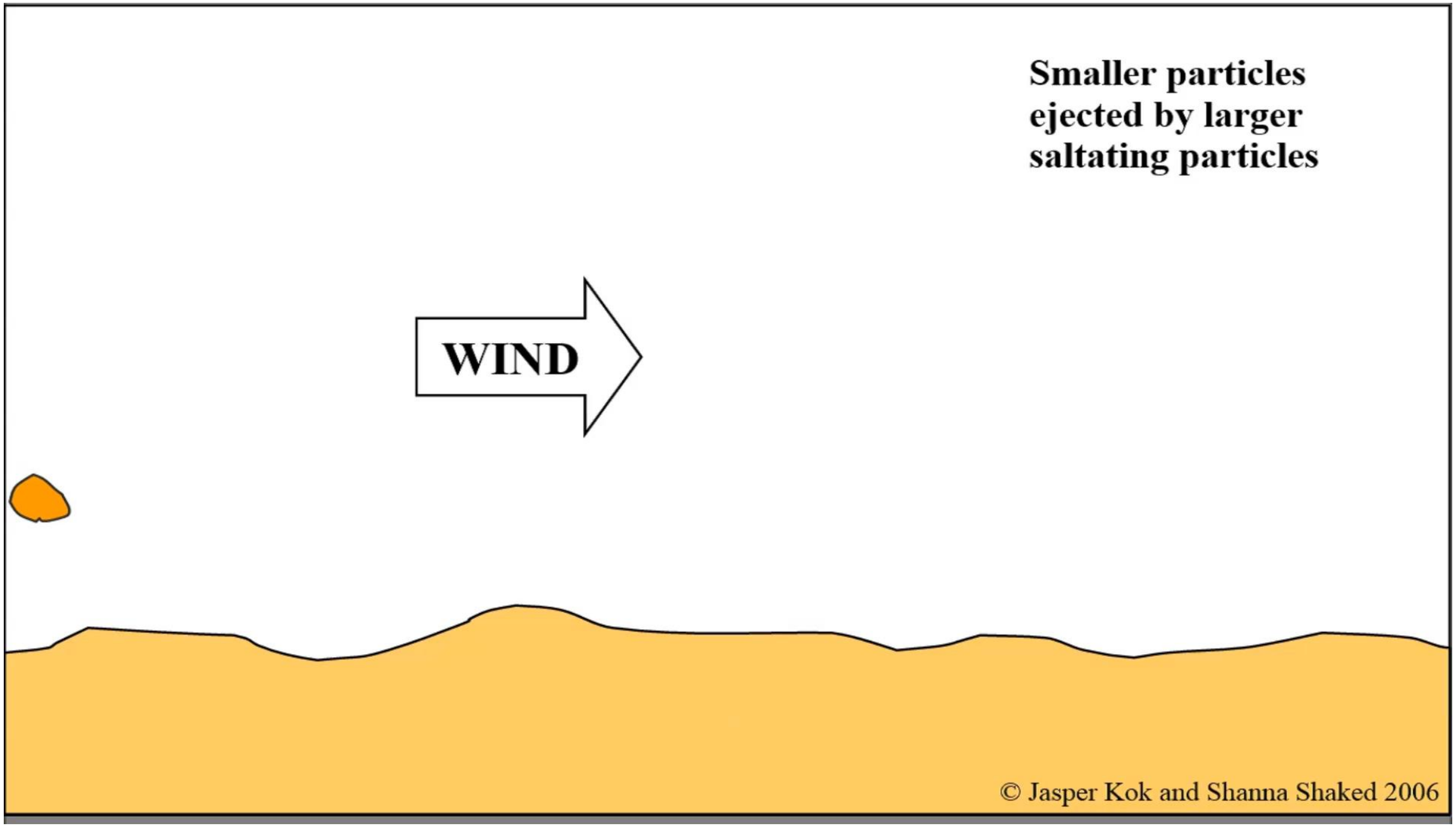
Photo credit: JPL/NASA

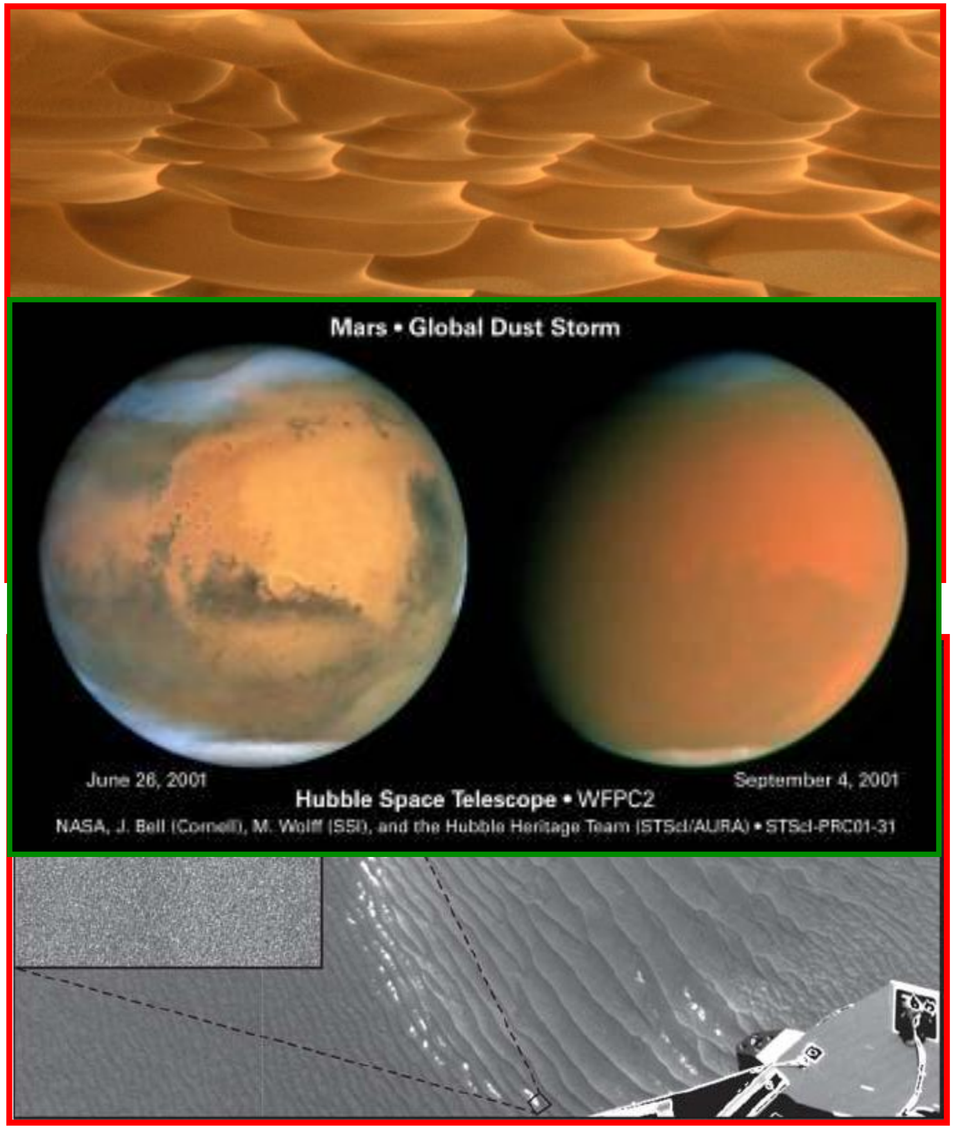
Saltation



- **Saltation** is the wind-driven hopping motion of sand grains (~200 μm)

Importance of saltation on Mars

- Saltation **creates dunes, ripples, and other bedforms**
  - Widespread on Mars
- Saltation emits dust and **likely plays important role in dust storms**
  - **Dust storms** and dust devils (tornado-like convective vortices) are **common** on Mars



Dust devils on Mars!

- Dust devils observed in 2005 by Spirit, one of the two Mars Exploration Rovers

Overview

- **'Classical' picture** of martian saltation
  - Unable to explain several long-standing **mysteries in martian landscape**

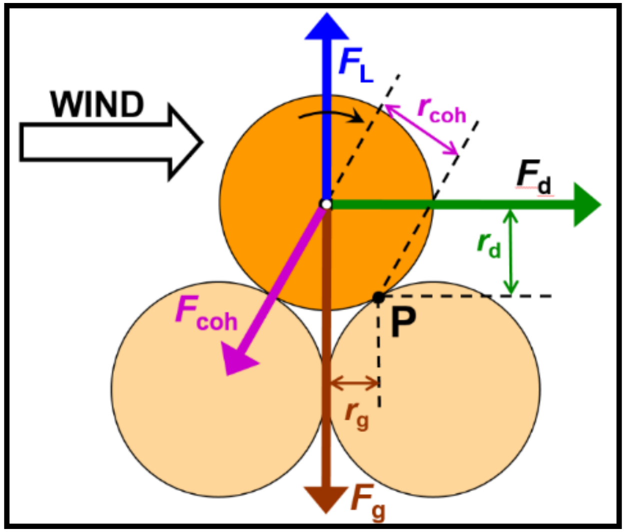
- Physically-based **model of saltation**

- **Solutions** to martian mysteries
  - Sand transport occurs at **much lower wind speeds**!
  - Sand trajectories are **much smaller**

When does sand move on Mars?

- Sand moves when threshold wind speed to lift sand is exceeded:
  $F_d r_d + F_L r_L >= F_{coh} r_{coh} + F_g r_g$

- **F_d and $F_L \propto u_*^2$**
  - **u_* = wind shear velocity**, proportional to wind speed
  - Value of u_* at which sand is lifted is u_{*ft} = the **"fluid threshold"**

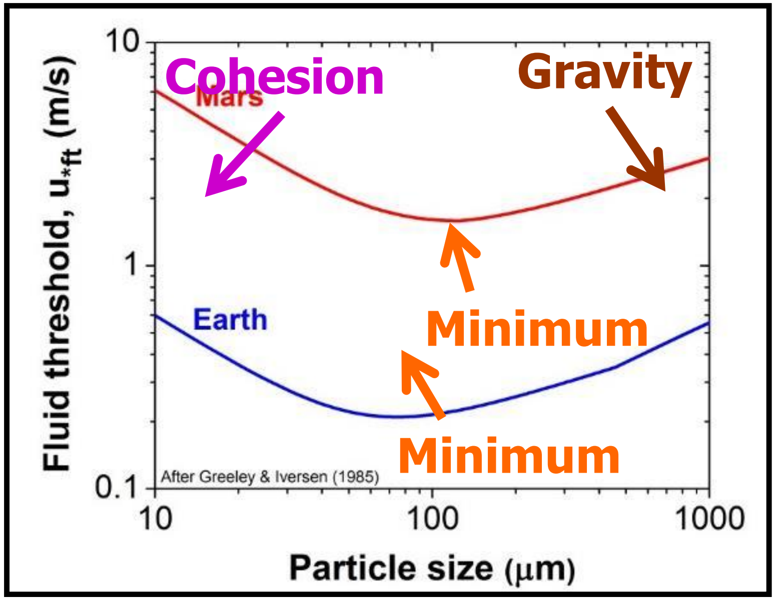


From Kok et al., Rep. Prog. Phys., 2012

- Sand of **~100 μm** is easiest to lift

- Martian air density is **only ~1 %** that of Earth

→ Martian **fluid threshold ~10x larger**, $u_{*ft} \approx 2$ m/s
  - = ~70 m/s at 10 m = 250 km/hour = category 5 hurricane!
  - Very **difficult to move sand** on Mars

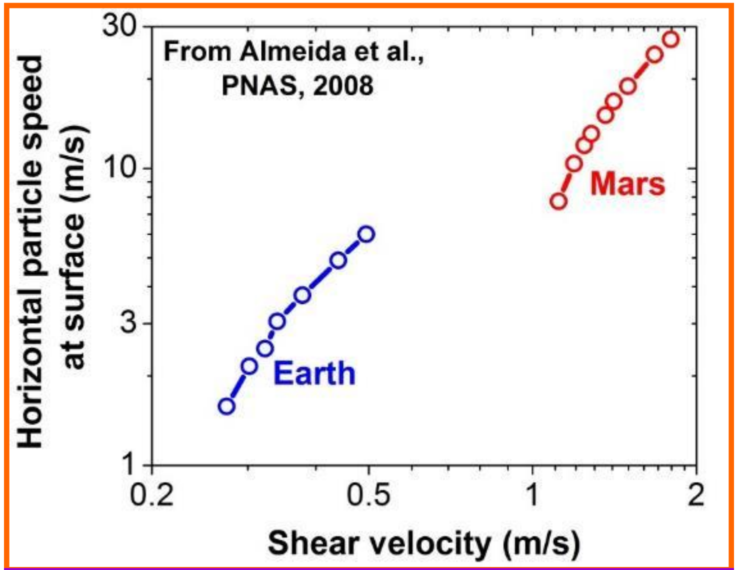


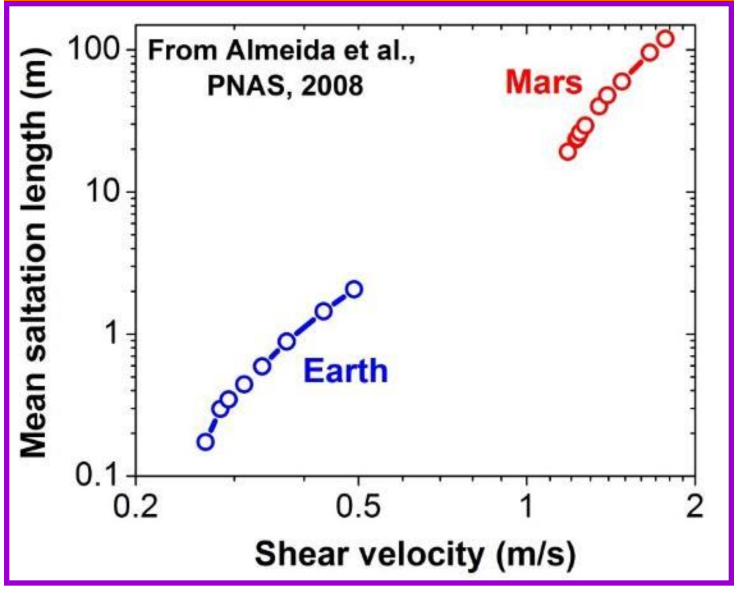
‘Classical’ Mars saltation theory: Large wind speed → giant saltation

- Previous studies assumed that **particle speed scales with wind speed** (e.g., Bagnold, 1941; Sagan, 1973)
  - ($V_x \sim u^*$)
- Martian saltation occurs at **large wind speed**

→ produces **‘giant’ saltation** (Sagan 1973, Almeida et al. 2008)

- **Giant particle speeds** (10-30 m/s at surface)
- **Giant hops** (tens to hundreds of meters)

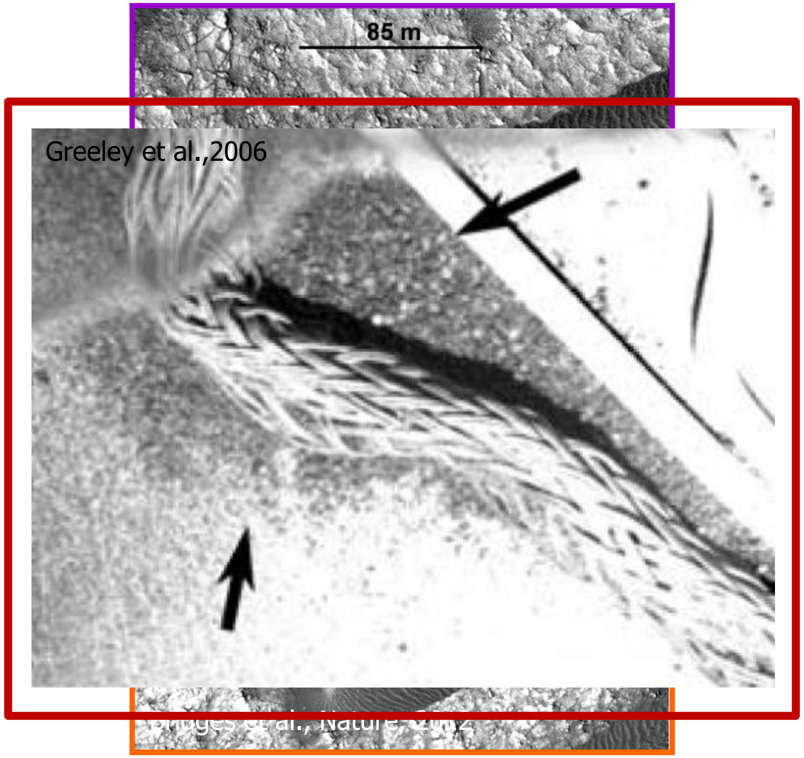


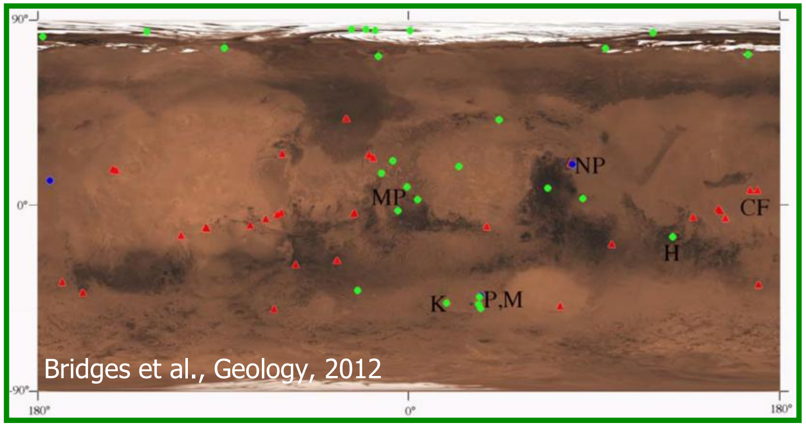


Mystery #1: Saltation occurs regularly on present-day Mars… but how?

- **Saltation occurs regularly** on martian surface
  - Widespread **movement of ripples…**
  - …and **dunes** (Bridges et al. 2012a, b)
  - **Sand accumulates on deck of rovers** (Greeley et al. 2006, Sullivan et al. 2008)

- But (sporadic) measurements and models indicate **wind rarely exceeds fluid threshold** (e.g., Zurek et al. 1992, Sullivan et al. 2000)
  - Then how does all this sand transport occur? (Kok, Nature, 2012)



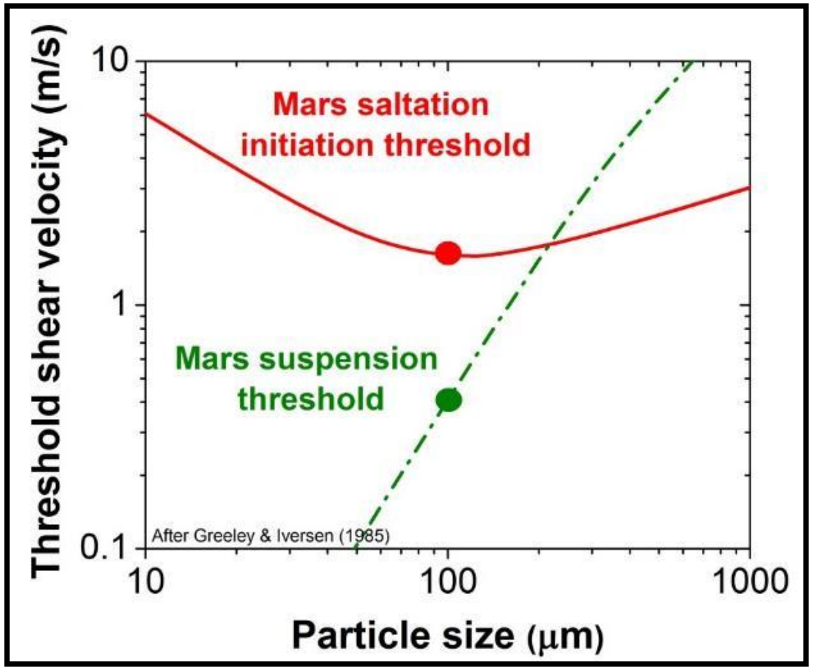


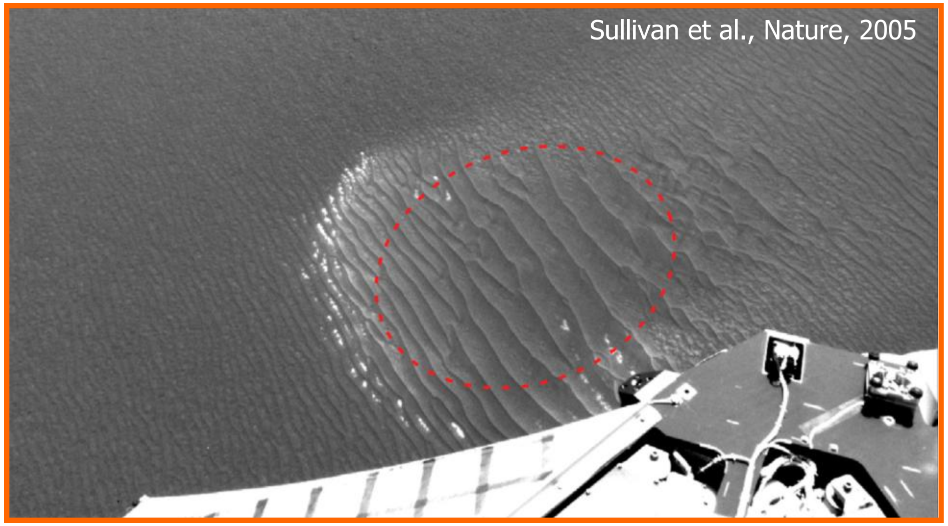
Bridges et al., Geology, 2012

Mystery #2: Very small grains form ripples! Shouldn't they be suspended?

- Mars rovers have found **ripples of 100 μm sand**
- But 100 μm **particles become suspended** well below saltation fluid threshold!
  - Criterion: suspension when $v_{terminal} <= u_*$ (Edgett & Christensen, 1991)

  → How can these ripples form?



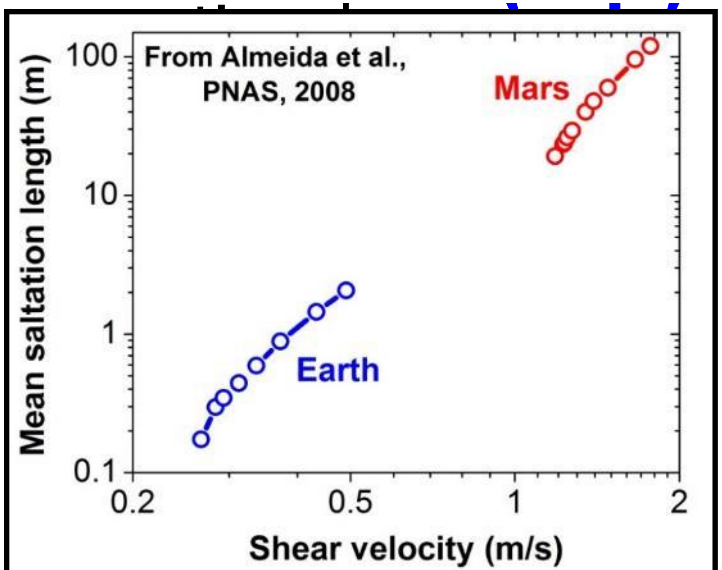


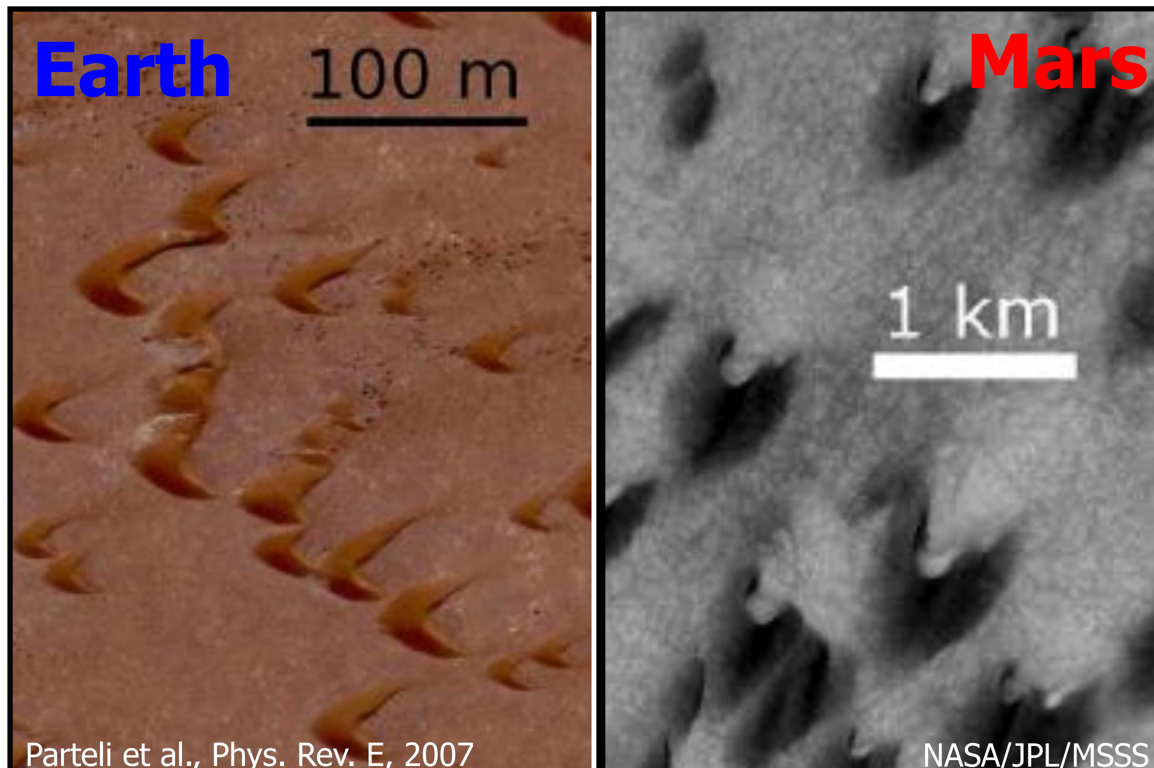
Mystery #3: Why are martian dunes relatively small?

- The minimal size of crescent-shaped ‘barchan’ dunes depends on the **length over which sand flux saturates**
  - This **‘saturation length’** increases with saltation hop length (Pähtz, Kok, Parteli, and Herrmann, PRL, 2013)

  → Minimal size of **martian barchan dunes should be much larger** (by over 2 orders of magnitude) than on Earth

- But minimum size of



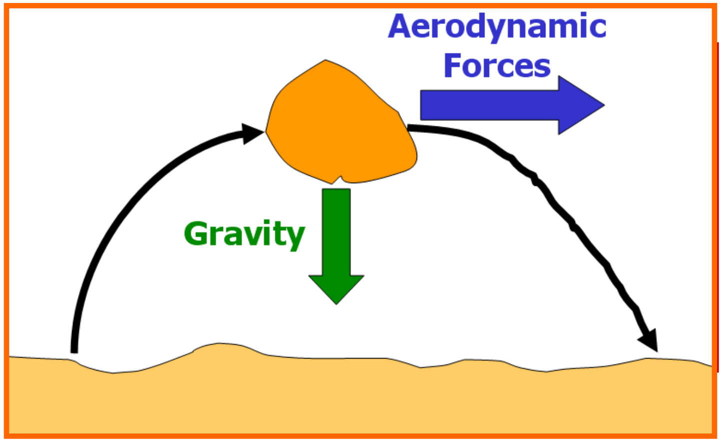


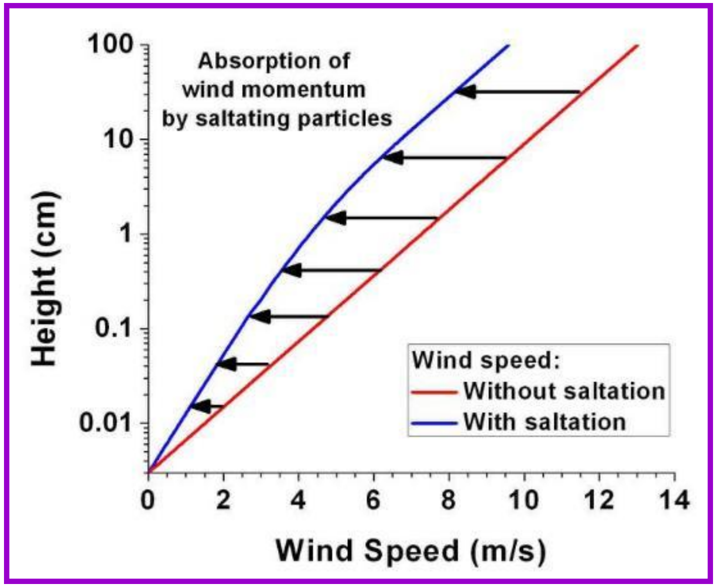
Overview

- ‘Classical’ picture of martian saltation
  - Unable to explain several long-standing mysteries in martian landscape
- Physically-based **model of saltation**
- Solutions to martian mysteries
  - Sand transport occurs at much lower wind speeds!
  - Sand moves with much lower particle speeds

COMprehensive SALTation model: COMSALT

- Model was coded in Matlab and is **freely available** (Kok and Renno, JGR, 2009)
- **Lagrangian simulation** of saltation trajectories (follows particle)
- **Eulerian simulation of fluid** velocity vertical profile (stationary reference frame)
- Physically-based **parameterization of splashing** of soil particles into saltation (more on this later)
- Model **iterates until steady-state** is reached
- The model was extensively **tested with terrestrial measurements** (Kok and Renno, 2009)
- The model is physically based and easily **adapted to martian conditions** (i.e., T ~ 220 K, P ~ 700 Pa)





1st model to reproduce Earth particle speeds

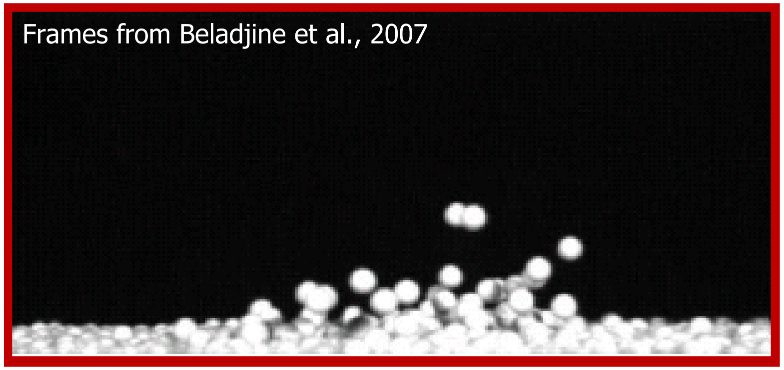
- Major advance over previous models is **realistic inclusion of splash**

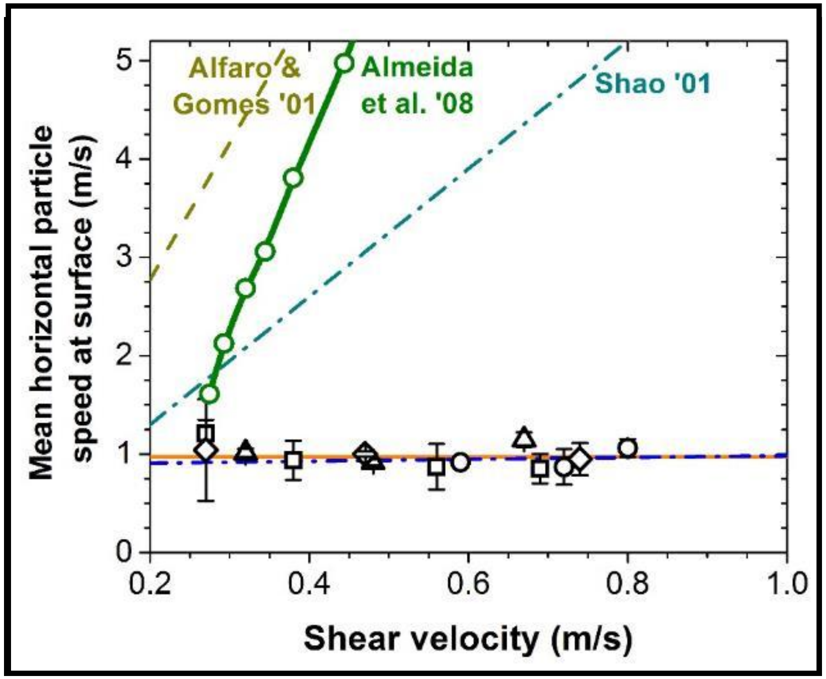
- Particle speeds at surface **constrained by splash**
  - Steady state: **constant particle concentration**

  →one particle leaving the bed for each particle impacting it

- Rebound of impacting particle and splashing of surface particle(s) **depends on impact velocity only** (not on wind speed!)
  - **Impact speed ~constant with wind speed!** (e.g., Kok et al. 2012)
  - Measurements confirm this
  - **Model** reproduces this

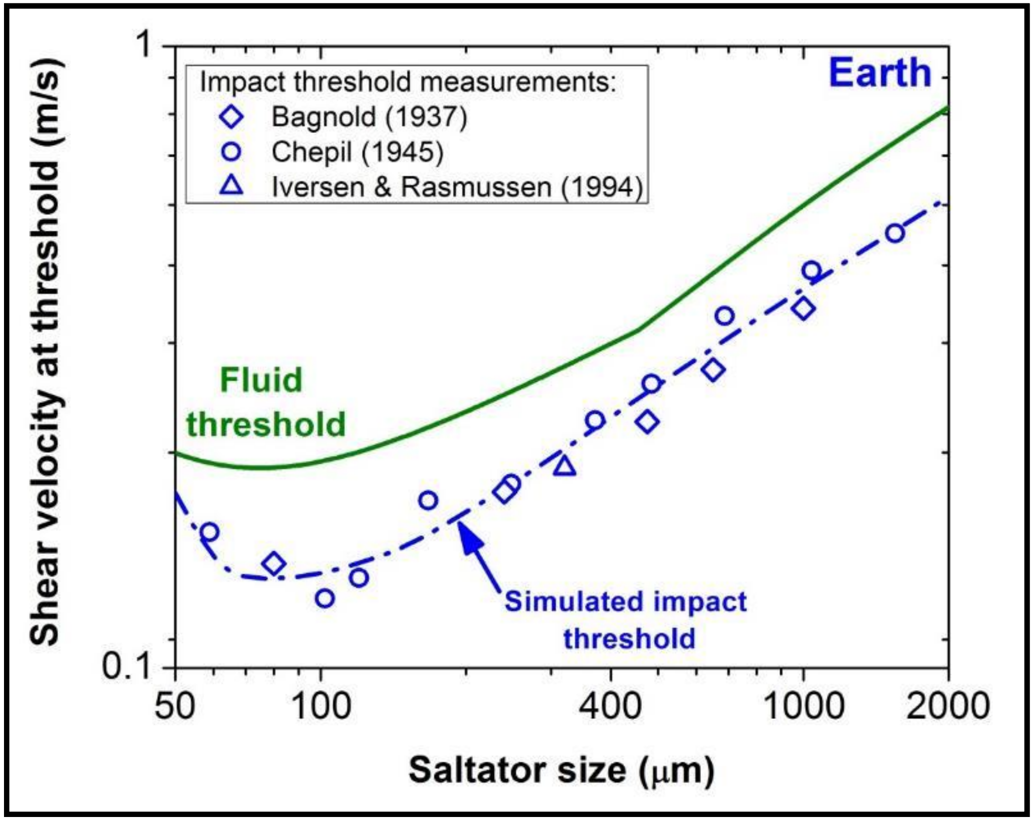
- '**Classical' saltation theory** and models do not account for splash and are in **disagreement with measurements**





1st model to reproduce Earth impact threshold

- '**Impact threshold**' = lowest wind speed at which saltation can be sustained by splashing
  - '**Fluid threshold**' = minimum wind speed to initiate saltation
- First model that **reproduces Earth impact threshold**



From Kok and Renno (JGR, 2009) and Kok et al. (ROP, 2012)

Overview

- ‘Classical’ picture of martian saltation
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- Physically-based model of saltation
- **Solutions** to martian mysteries
  - Sand transport occurs at **much lower wind speeds**!
  - Sand moves with **much lower particle speeds**

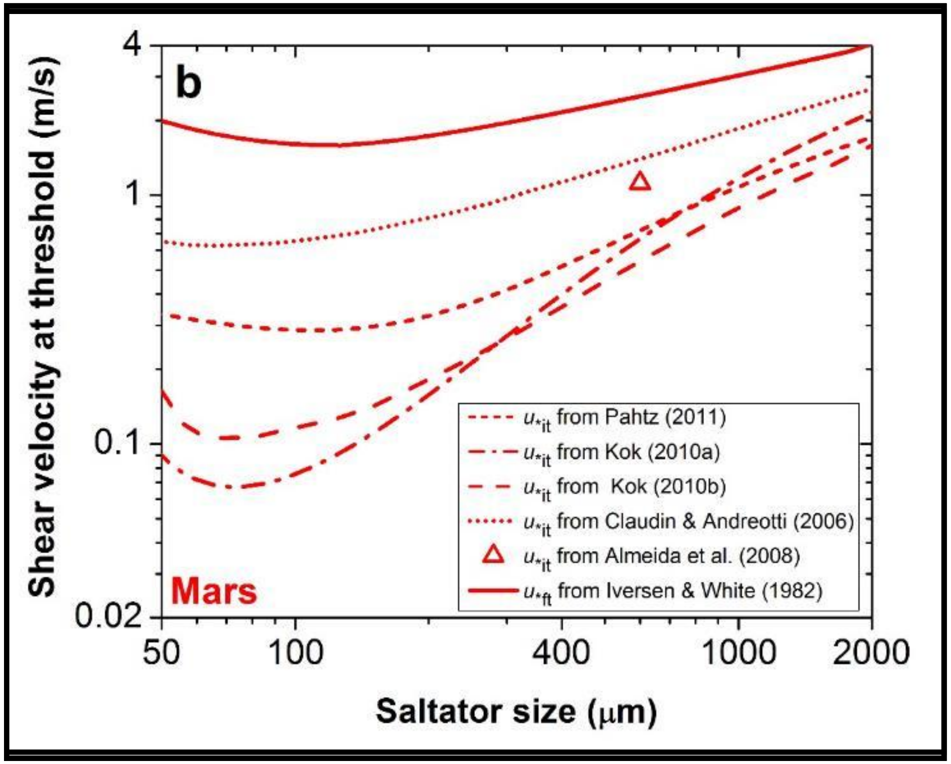
Martian impact threshold is very small

- Mars impact threshold is **same order of magnitude as Earth**
  - Order of magnitude **below the fluid threshold!**
  - **Analytical calculation** confirms results
    - Uses **steady-state condition** that number of particles lost to soil must equal number of ejected particles

- Hysteresis occurs because:
  - Low gravity and low vertical fluid drag on Mars causes **particles to reach large heights**
  - Wind speed increases with height

  → Particles easily gain enough speed to sustain saltation, even at weak winds

- Other theoretical and numerical studies have confirmed this



From Kok, Phys. Rev. Lett., 2010a and Kok, Geophys. Res. Lett., 2010b

From Kok et al., Rep. Prog. Phys., 2012

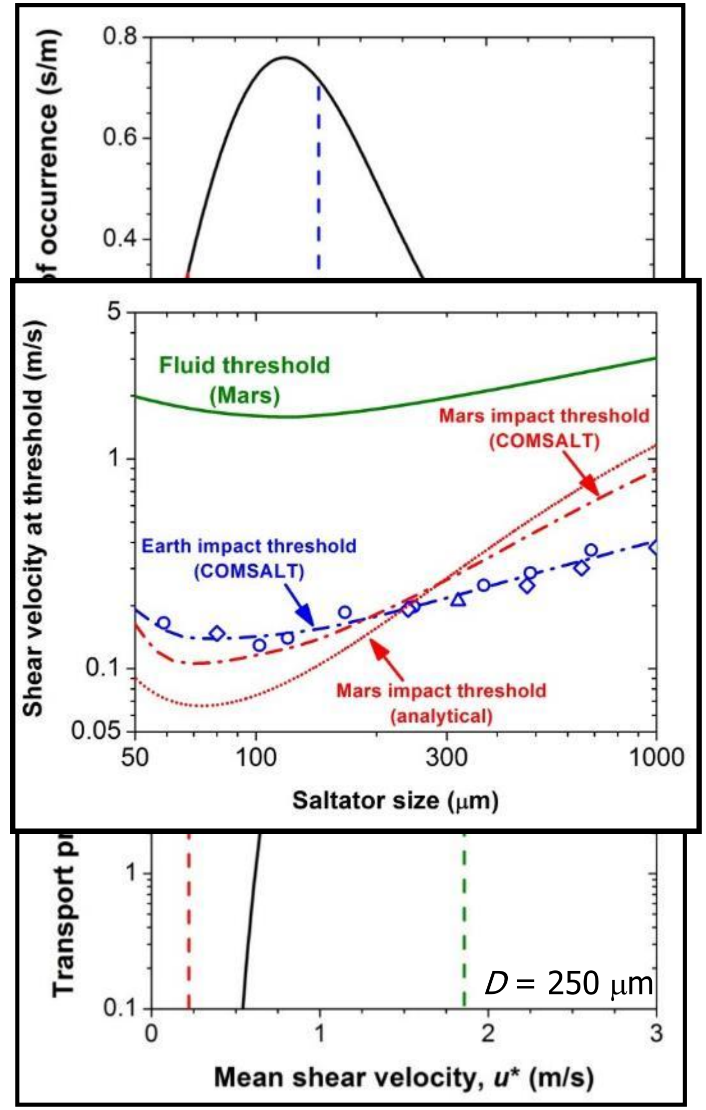
Solution to mystery #1: Saltation possible for much lower wind speeds

- Occurrence of saltation between impact and fluid thresholds depends on wind history (**hysteresis**)
- Temporal variation of wind speed follows **Weibull distribution** (Michaels, 2006)
- Consider 'grid box' with mean u^* = 1 m/s
- **Probability** that saltation transport occurs:

$$P_{tr} = P_W\left(u^* > u^*_{it}\right) + P_W\left(u^*_{ft} < u^* < u^*_{it}\right)\frac{P_W\left(u^* > u^*_{ft}\right)}{P_W\left(u^* < u^*_{it}\right) + P_W\left(u^* > u^*_{ft}\right)}$$

Probability that $u^* > u^*_{ft}$ | **Probability that $u^*_{it} < u^* < u^*_{ft}$** | **Probability that $u^* > u^*_{fl}$ more recently than $u^* < u^*_{it}$**

- **Saltation occurs well below fluid threshold** because of hysteresis effect!!
  - Helps explain saltation occurrence despite high fluid threshold (Kok, Nature, 2012)



From Kok, Phys. Rev. Lett., 2010a and Kok, Geophys. Res. Lett., 2010b

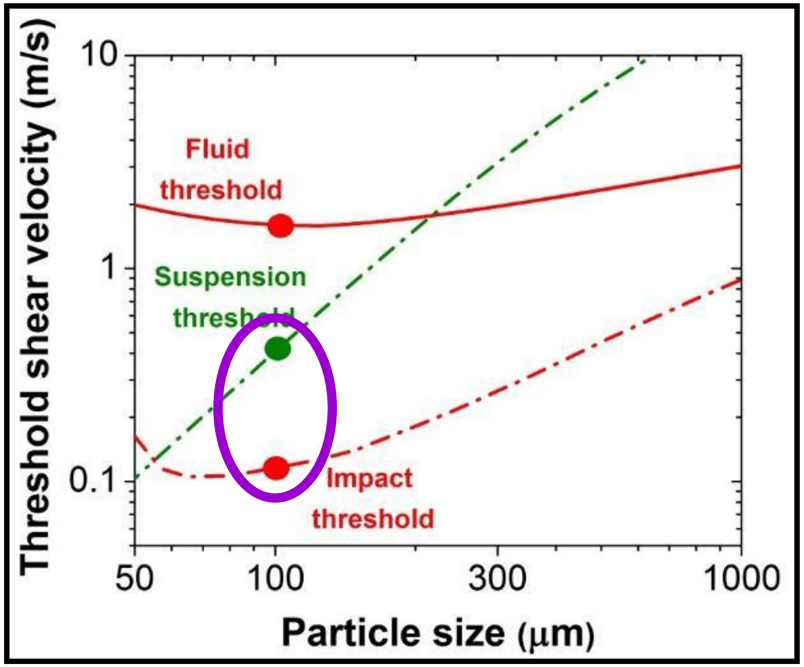
Solution to mystery #2: Hysteresis allows 100 μm bedforms to be stable

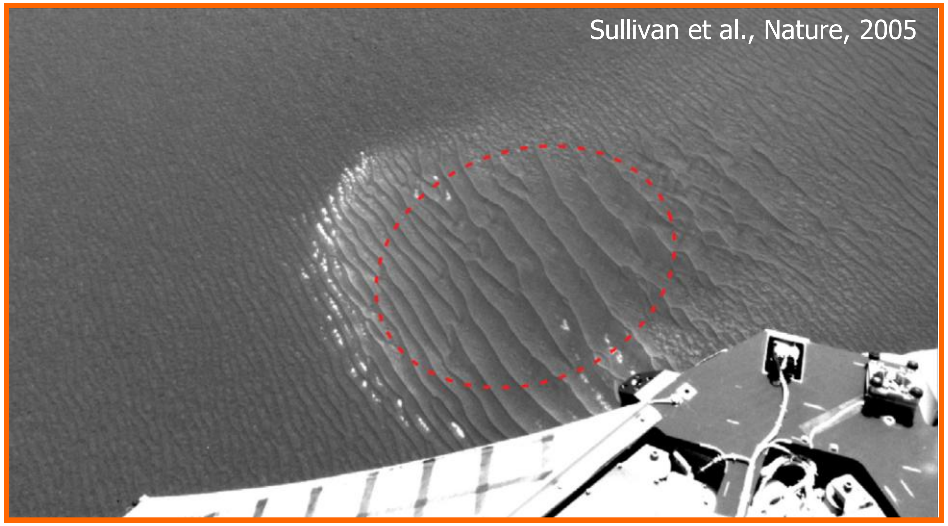
- Mars rovers found **ripples of 100 μm sand**
- But 100 μm **particles become suspended** well below saltation fluid threshold!
  - Criterion: suspension when $v_{terminal} <= u*$

  → How can these ripples form?

- Hypothesis:
  - Rare, high-speed eddy lifts and suspends a few particles
  - Particles quickly exit the eddy
  - Because of **low impact threshold,** can saltate in background wind

    → can form ripples





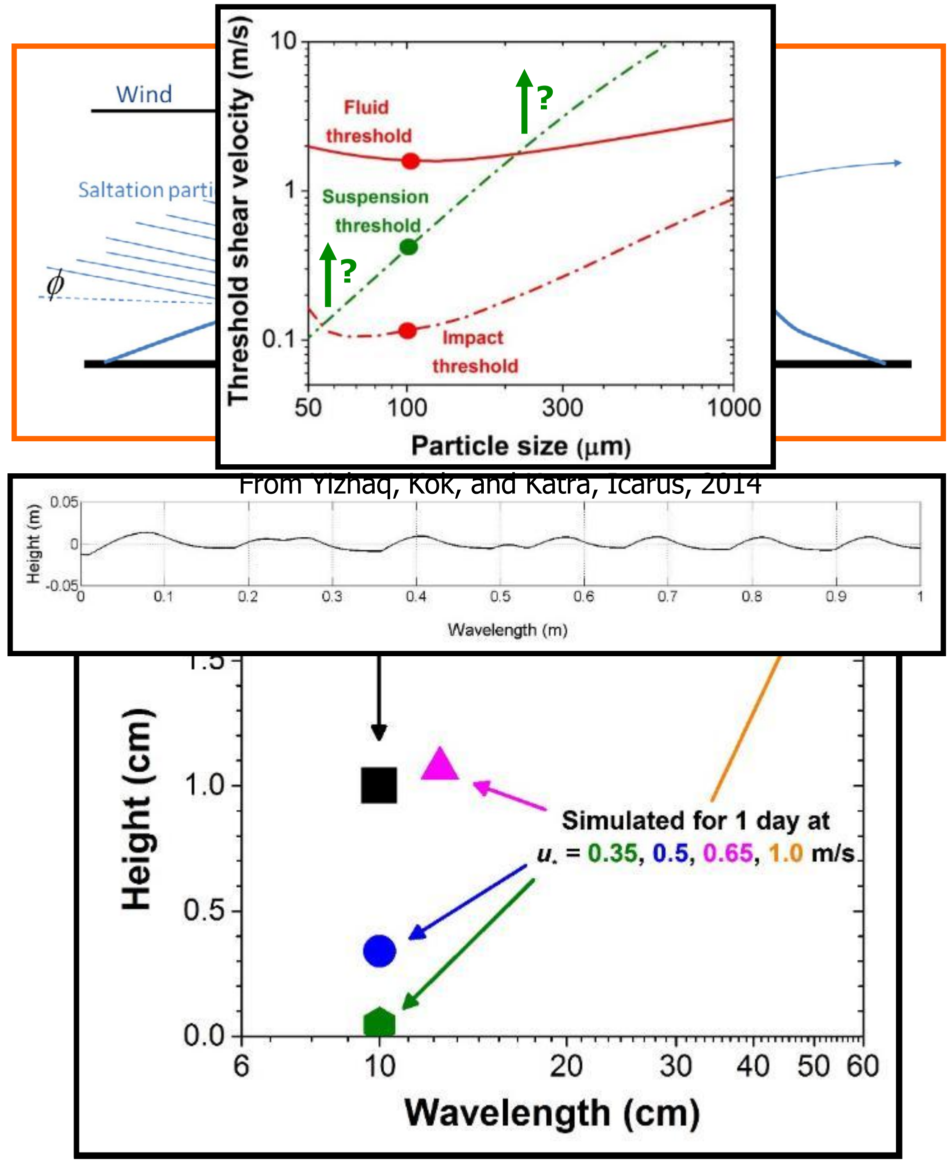
Solution to mystery #2: Hysteresis allows 100 μm bedforms to be stable

- Tested hypothesis by coupling COMSALT to Hezi Yizhaq's **ripple model** (Yizhaq et al., 2004)
  - COMSALT provides saltation properties and *reptation* hop lengths
  - Ripple model simulates resulting **evolution of ripples**

- **Ripples can form** for $u_{*it} < u_* < u_{*ft}$ because of **hysteresis**

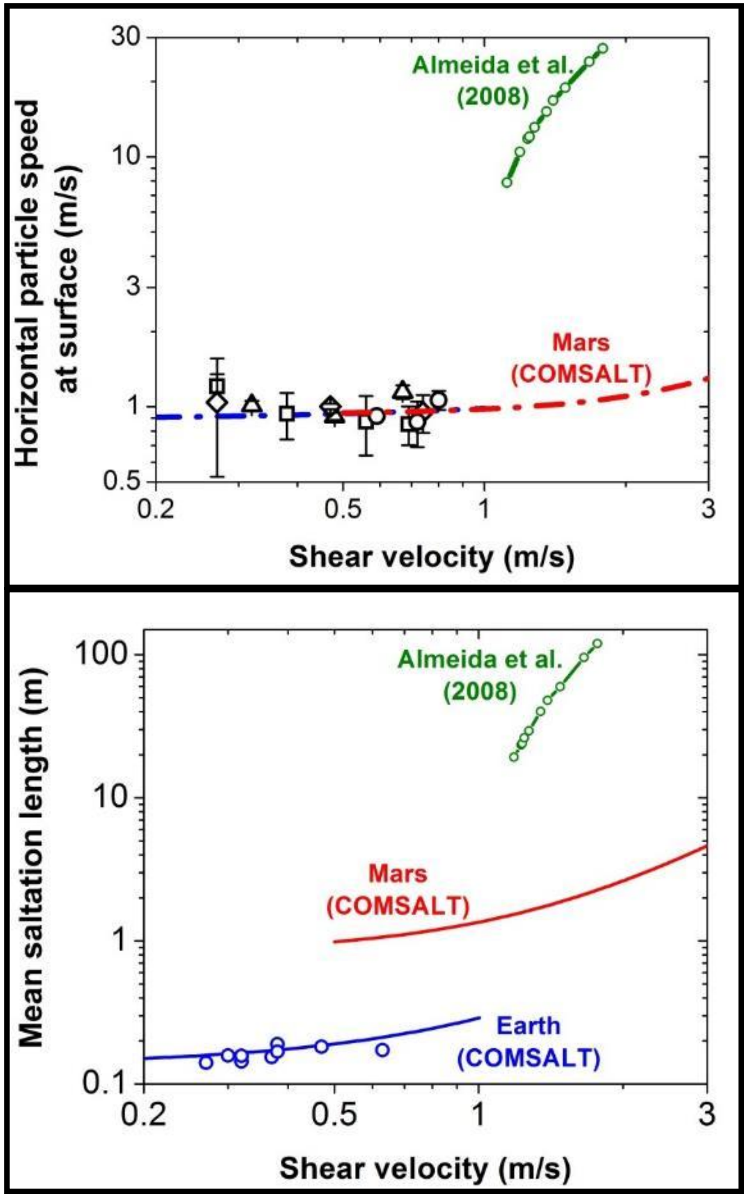
- **Observed ripples reproduced** for $0.35 < u_* < 1$ m/s
  - Simulation time at which measurements are matched depends on u_*

- Saltation occurs up to ~1 m/s
  - Suspension criteria ($v_{terminal} <= u*$) might not be appropriate for Mars (Sullivan et al., 2005)



Particle speeds and trajectories on Mars much smaller than thought

- Mean **impact speed** is a **property of particle bed**, NOT of fluid!
  - Mean impact speed on **Mars must be similar** for similar sand particles!
  - **'Classical' theory overestimates** particle speeds by over order of magnitude
- Particle trajectories are thus also much smaller than thought
  - But still ~order of magnitude larger than on Earth because of **lower gravity and vertical drag**
  - **'Classical' theory overestimates** particle trajectories by over order of magnitude



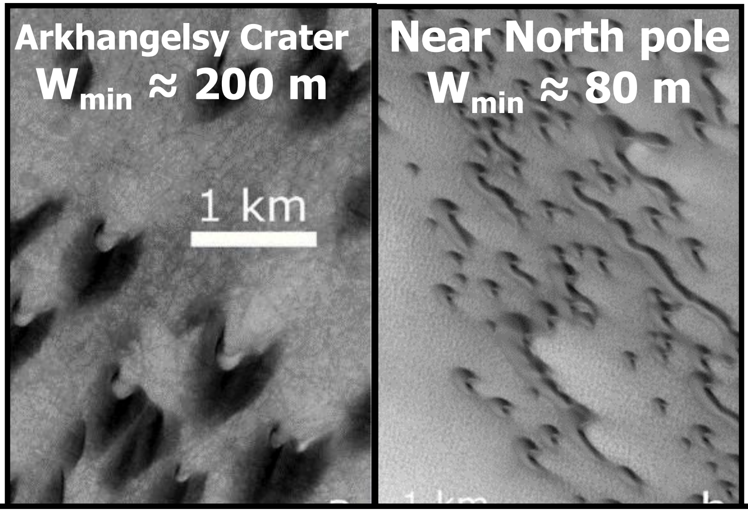
Solution to mystery #3: Smaller trajectories = smaller dunes

- Minimal size **W_{min}** of martian barchan dunes depends on sand flux **saturation length (L_s)**
  - **$W_{min} \approx 12\ L_s$** (Parteli et al., 2007)

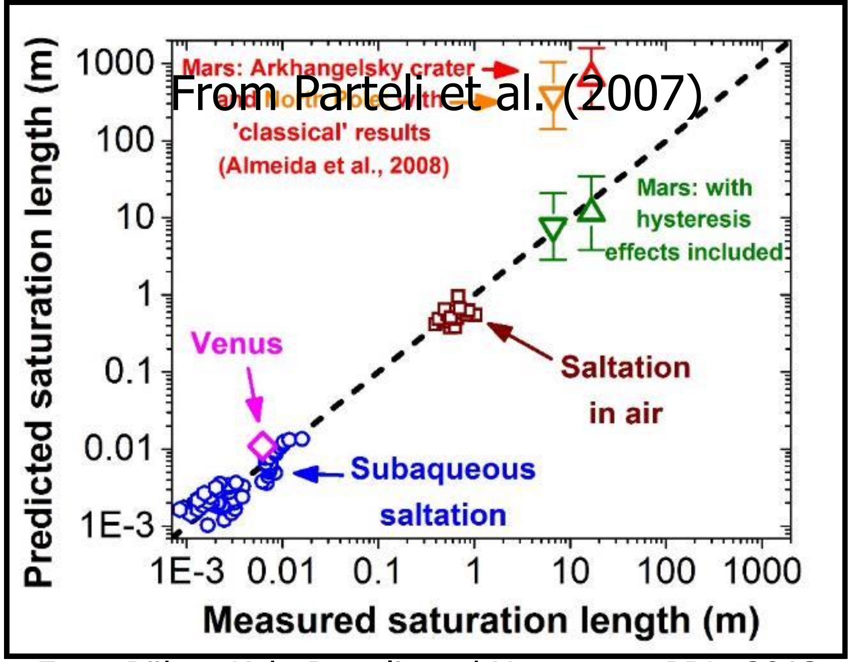
- Developed analytical **model of saturation length** (Pähtz, Kok, Parteli, and Herrmann, PRL, 2013)
  - Consistent with measurements in both **air** and **water**
  - And for **Venus conditions**

- **Classical theory** overestimates Martian saltation trajectories and thus the saturation length

- Accounting for **hysteresis effects** on saltation trajectories results in **~correct saturation length**
  - Uses D = 100 – 600 μm (Bourke et al., 2010)



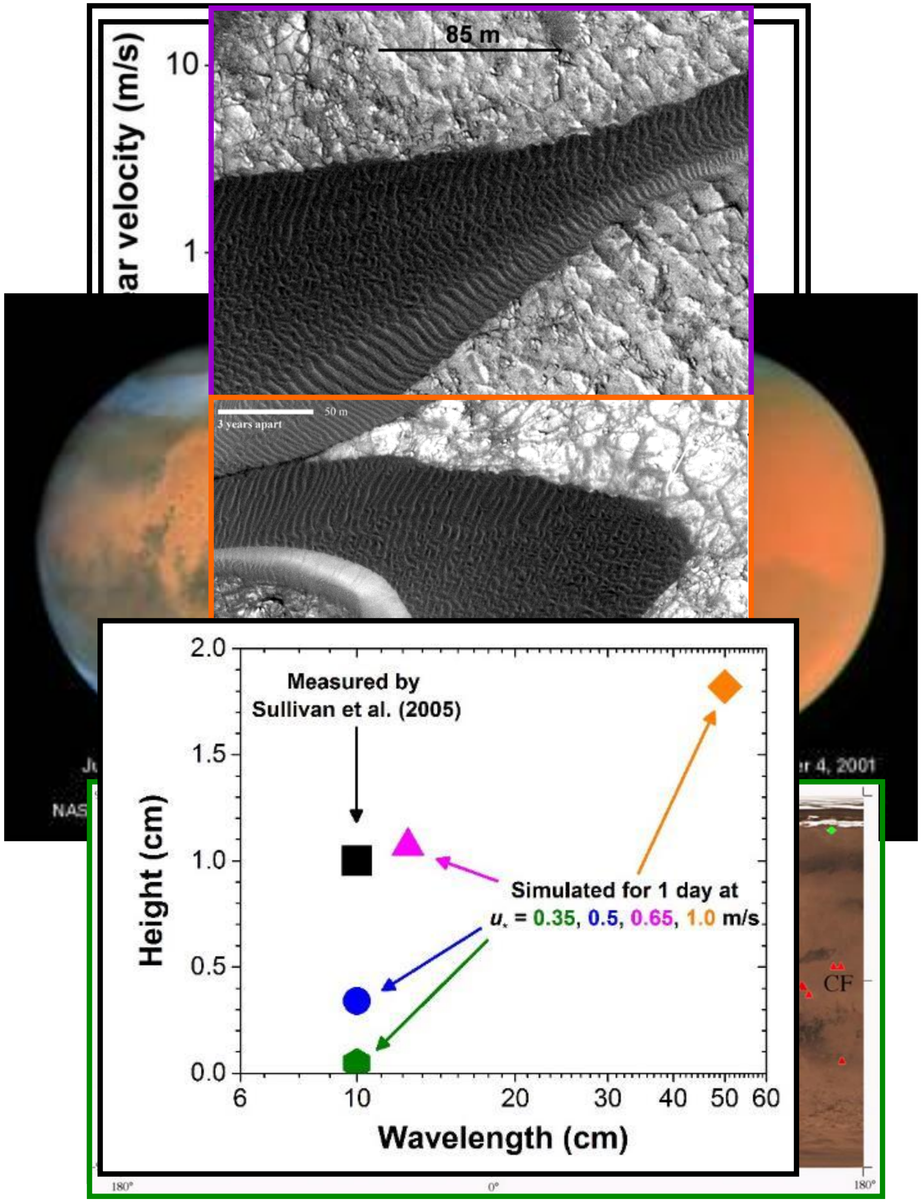
From Parteli et al. (2007)



From Pähtz, Kok, Parteli, and Herrmann, PRL, 2013

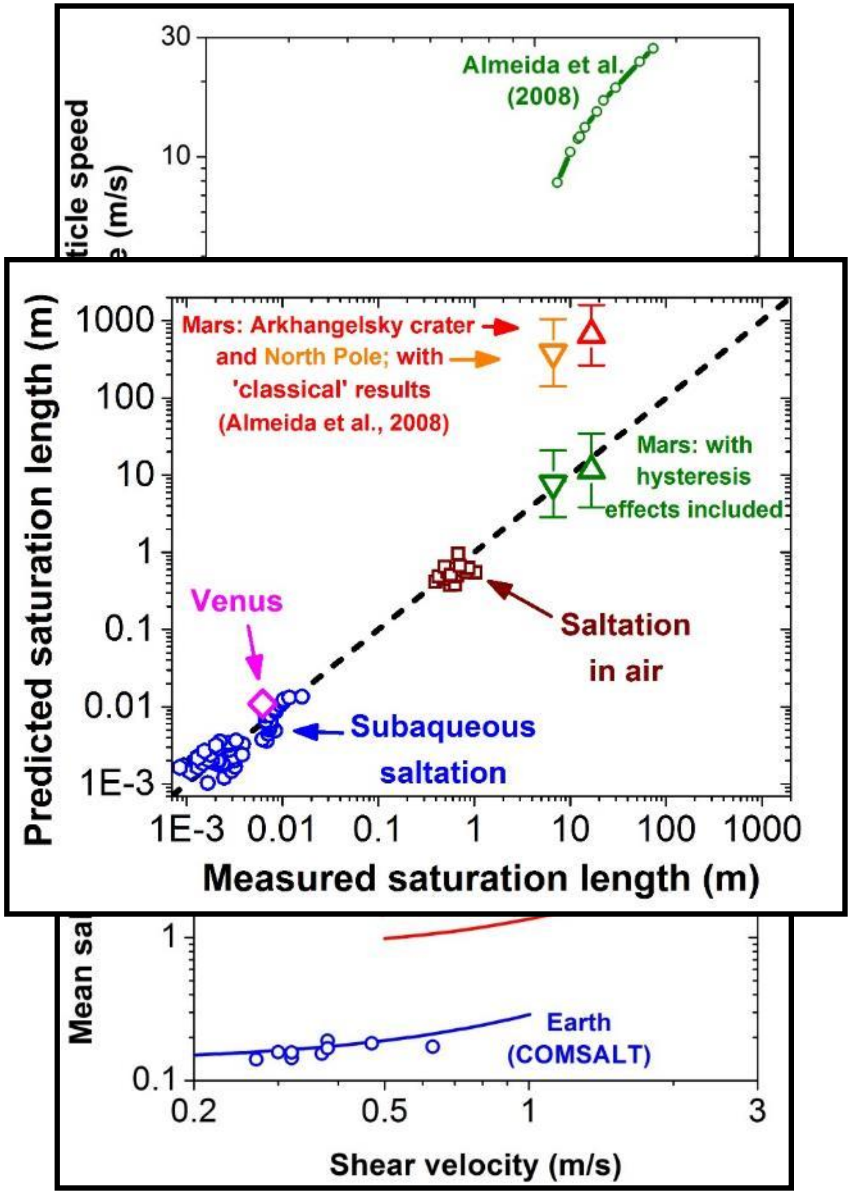
Summary and conclusions: saltation possible for much lower wind speeds!

- Impact threshold **order of magnitude** below fluid threshold on Mars
- **Sand transport occurs for much lower wind speeds** than previously thought
  - Needs to be experimentally verified
  - (Partially?) **resolves discrepancy** that saltation occurs regularly on Mars but rarely have $u^* > u^*_{ft}$
  - Explains **stability of 100 μm ripples** on Mars
- Possibly important for **dust storms** and dust emission



Summary and conclusions: smaller saltation trajectories and dunes

- Martian **particle speed much smaller** than previously thought
  - Particle speed at surface is determined by particle bed and is thus **similar on Earth and Mars**
  - Results in much **smaller saltation trajectories**
- Explains **smaller-than-expected** martian dunes



Thank you!

Relevant papers:

Almeida, M. P., et al. (2008), Giant saltation on Mars, *Proc. Natl. Acad. Sci. U. S. A.*, 105(17), 6222–6226.

Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes* (New York: Methuen).

Greeley, R., et al. (2006), Gusev crater: Wind-related features and processes observed by the Mars Exploration Rover Spirit, *J. Geophys. Res*. 111, E02S09.

Kok, J. F., and N. O. Renno (2009), A comprehensive numerical model of steady-state saltation (COMSALT), *J. Geophys. Res.*, 114, D17204.

Kok, J. F. (2010), Difference in wind speeds required for initiation versus continuation of sand transport on Mars: Implications for dunes and dust storms, *Phys. Rev. Lett.*, 104, 074502.

Kok, J. F. (2010), An improved parameterization of wind-blown sand flux on Mars that includes the effect of hysteresis, *Geophys. Res. Lett.*, 37, L12202.

Kok, J. F., E. J. R. Parteli, T. I. Michaels, and D. Bou Karam (2012), The physics of wind-blown sand and dust, *Reports on Progress in Physics*, in review. Online at http://arxiv.org/abs/1201.4353v1

Kok, J. F. (2012), Martian sand blowing in the wind, Nature, 485, 312-3.

Kroy, K., S. Fischer, and B. Obermayer (2005), The shape of barchans, *J. Phys. Condens. Matter,* 17, S1229.

Michaels, T. I. (2006), Numerical modeling of Mars dust devils: Albedo track generation, *Geophys. Res. Lett.*, 33, L19S08.

Pähtz, T, J. F. Kok, and H. J. Herrmann (2012), The apparent roughness of moving sand transported by wind, *New Journal of Physics*, 14, 043035.

Pähtz, T, J. F. Kok, E. J. R. Parteli, and H. J. Herrmann (2013), Flux saturation length of sediment transport, *Physical Review Letters*, 111, 218002.

Parteli, E. J. R., and H. J. Herrmann (2007), Dune formation on the present Mars, *Physical Review E,* 76, 041307.

Presley, M. A., and P. R. Christensen (1997), Thermal conductivity measurements of particulate materials 2. Results, *J. Geophys. Res.* 102 (E3), 6551-6566.

Sagan, C. (1973), Sandstorms and Eolian Erosion on Mars, *J. Geophys. Res,*, 78, 4155-61.

Sullivan R., et al. (2005), Aeolian processes at the Mars Exploration Rover Meridiani Planum landing site, *Nature,* 436, 58-61.

Sullivan R., et al (2008), Wind-driven particle mobility on mars: Insights from Mars Exploration Rover observations at "El Dorado" and surroundings at Gusev Crater, *J. Geophys. Res.,* 113, E06S07.

Yizhaq, H., Balmforth, N.J. and Provenzale, A. (2004). Blown by wind: Nonlinear dynamics of aeolian sand ripples. Physica D, 195, 207-228.

Yizhaq, H., J. F. Kok, and I. Katra (2014), Basaltic sand ripples at Eagle crater as indirect evidence for the hysteresis effect in Martian saltation, Icarus, http://dx.doi.org/10.1016/j.icarus.2013.08.006.