CONTROLS ON AND IMPLICATIONS OF AEOLIAN GEOMORPHOLOGY ON COMET 67P.
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Introduction: Thomas et al. [1] described putative aeolian dunes and/or ripples and wind shadows on the surface of Comet 67P as observed by ESA's spacecraft Rosetta (Figure 1). Purportedly, these formed from cometary jets blowing laterally across the surface and mobilizing surface sediment. This exploratory abstract considers some of the controls and implications of cometary aeolian bedforms.

Prior to this discovery, Cheng et al. [2] invoked aeolian activity to explain much of the geomorphology on comets Wild 2, Hartley 2, and Tempel 1. For Comet Hartley 2, they predicted fluid threshold friction speeds u_{*ft} of ~5-96 m/s with higher friction speeds required to mobilize smaller particles due to their higher susceptibility to cohesive forces. This threshold velocity is substantially below jet velocities modeled for Comet Hyakutake of ~500-1500 m/s [3]. Additionally, most cometary outgassing occurs from non-jet amorphous outflow that could likely have a lateral velocity component.

Here, using several simple models, we consider the hypothesis that cometary jets can mobilize sediment across the surface, and that particles can be retained on the comet by gravity and cohesion. Thus, the putative aeolian bedforms could indeed be aeolian in nature; whether they are dunes or ripples is not conclusive, though we think ripples are more likely.

Aeolian Theory & Results: Particle speeds at the surface are relatively insensitive to changes in friction shear velocity u_* ([4] and references therein); thus winds much faster than u_{*ft} will generally not produce faster saltating particles. Note that once fluid shear stress initiates saltation, saltating particles are the dominant means of lofting more saltators and not fluid shear stress alone [4]. Additionally, ballistic reptation [6]—which is not a fluid mechanical phenomenon—can launch lower energy grains when a saltating grain impacts the comet's surface. This allows that ripples may be the dominant aeolian bedform on Comet 67P.

Terrestrial Model Applied to Comet 67P: Iverson et al. [7] presented an expression for u_{*ft}, where the variables are described in Table 1:

$$u_{*ft} = A_N \sqrt{\frac{\rho_p - \rho_a}{\rho_a} g D + \frac{\gamma}{\rho_a D}}.$$

The actual wind velocity U at a given height is then expressed by

$$U = \frac{u_*}{0.4} \ln\left(\frac{z}{z_{0L}}\right).$$

where we take $u_* = u_{*ft}$. This assumes a boundary layer profile.

By varying the roughness parameter z_{0L} as indicated in Table 1, we obtain wind speed velocity profiles shown in Figures 2 and 3 assuming the wind is at fluid threshold, calculated at 42.3 m/s. Interestingly, this value is within the range independently calculated for Hartley 2 by [2].

Table 1. Constants and results of terrestrial aeolian theory applied to Comet 67P

A_N	Proportionality Constant (changes for particle friction Re)	0.111
γ	Interparticle strength parameter	2.9×10^{-4} (Kok et al., 2012; value for terrestrial dust & sand)
ρ_p	Water ice density	917 kg/m^3
ρ_a	Air density	2×10^{-5} kg/m^3
g	Gravitation acceleration	10^{-3} m/s^2
D	Particle size	100 µm, 500 µm
z_{0L}	Lettau (1969) aerodynamic roughness height	0.1, 0.01, 0.001 m (varied in calculation)
u_{*ft}	Fluid threshold fiction speed (calculated from above)	42.3 m/s

Jet Velocities: Our simple terrestrial aeolian model as well as [2]'s model agree and are less than the predicted jet velocities of ~450 m/s calculated from

$$V_{\text{outflow}} = \frac{0.65}{\sqrt{r_h}}$$

where r_h is the solar distance in AU and we use $r_h = 2$. Note this is on the low end predicted by [3].

Other Wind Considerations: From the comet's physical size and rotation rate, we find that only a 0.3 m/s wind could be created from rotating within its own coma; we therefore do not consider this a substantial contributor to aeolian dynamics.

While gas velocities are well above escape velocity, mobilized particles would only attain a fraction of this speed and could remain gravitationally bound to the comet for grain speeds less than the escape velocity of 0.9 m/s [5].

Differential diurnal heating of the comet may also contribute to circum-cometary winds that could contribute a lateral component to other wind sources.

Discussion & Conclusion: *Saltation versus Reptation/Dunes versus Ripples:* As opposed to dunes, which are formed from saltation, the aeolian features on 67P may be giant aeolian ripples caused by reptation. This would allow saltating particles—even those moving above escape velocity—to still occasionally re-impact the comet (possible given the comet's irregular shape) and locally disturb particles on lower energy "hops" where the weak gravity could easily recapture the particles. Additionally, particle speeds necessary to create aeolian bedforms can be used to place upper constraints on grain cohesion.

Conclusion: We have considered that it is possible to mobilize gravitationally-bound sediment on comets and therefore to form aeolian bedforms. Laterally-blowing cometary winds—possibly from jets and/or amorphous outflow—mobilize saltating particles, which can in turn mobilize both saltating and reptating particles, both of which could be re-accreted even in the comet's week gravity. Since reptating particles are slower than saltating particles, it is less likely that they will gravitationally escape; thus the bedforms are more likely to be ripples than dunes. Furthermore, grain energies and values for u_{*ft} place upper bounds on grain cohesion, suggesting that cohesion may be quite low.

Future work is needed to quantitatively constrain grain energies and cohesion on comets. If Rosetta's long-term observations reveal bedform movement, such constraints may be within reach.

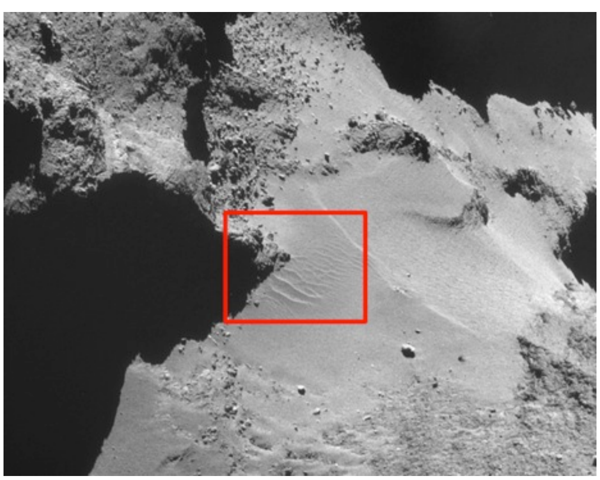

Figure 1. Putative dunes on Comet 67P. Length of the longest "dune" (at the bottom) is ~50 m. Credit: ESA/Rosetta/NavCam/Damia Bouic/Emily Lakdawalla.

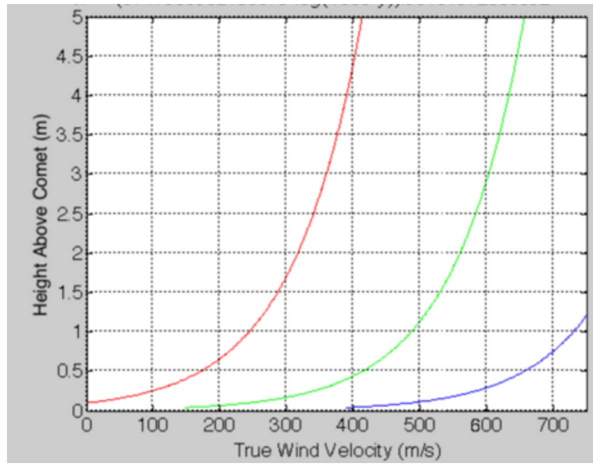

Figure 2. Wind height profiles for 100 μm diameter water ice grains. The only other varied parameter is surface roughness; red (left) = 0.1 m, green (middle) = 0.01 m, and blue (right) = 0.001 m.

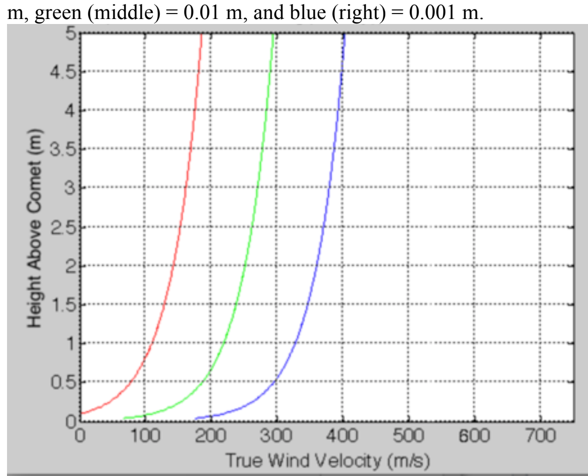

Figure 3. Wind height profiles for 500 μm diameter water ice grains. The only other varied parameter is surface roughness; red (left) = 0.1 m, green (middle) = 0.01 m, and blue (right) = 0.001 m.

References: [1] Thomas, N., et al., (2015) *Science*, 347, DOI: 10.1126/science.aaa0440. [2] Cheng, A. F., et al., (2013) *Icarus*, 222, 808–817, http://dx.doi.org/10.1016/j.icarus.2012.10.004. [3] Combi, M.R., et al., (2005) *in Comets II*, p. 523-552. [4] Kok, J.F., et al., (2012), *Reports in Progress in Physics*, 75, doi:10.1088/0034-4885/75/10/106901. [5] Sierks, H., et al., (2015), *Science*, 347, DOI: 10.1126/science.aaa1044. [6] Anderson, R.S., (1987), *Sedimentology*, 34, 943-956. [7] Iverson, J.D., et al. (1987), *Sedimentology*, 34, 699-706.