GIANT RIPPLES ON COMET 67P SCULPTED BY THERMAL WIND.

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Introduction: The OSIRIS camera on board the ESA's Rosetta spacecraft has revealed unexpected bedforms (Fig 1) on the comet 67P/Churyumov-Gerasimenko [1], whose features suggest that they belong to the family of ripples and dunes [2]. However, the existence of sedimentary bedforms on a comet comes as a surprise: it requires sediment transport along the surface, i.e. erosion and deposition of particles. When heated by the sun, the ice at the surface of comets sublimates into gas. As gravity is extremely small, g=2. 10^{-4} m/s^2, due to the kilometer scale of the comet [3], the escape velocity is much smaller than the typical thermal velocity. Outgassing therefore feeds an extremely rarefied atmosphere, called the coma, around the nucleus. This gas envelope expands radially. By contrast, ripples and dunes are formed by fluid flows parallel to the surface, dense enough to sustain sediment transport. The presence of these apparent dunes therefore challenges the common views of surface processes on comets and raises several questions. What could be the origin of the vapor flow exceeding the sediment transport velocity threshold? How could the particles of the bed remain confined to the surface of the comet rather than being ejected into the coma?

Outgassing and thermal winds: We have modeled both seasonal and diurnal time variations of the atmosphere characteristics in a simplified spherical geometry. At perihelion, we find that the pressure drops by ten orders of magnitude from day to night. The comet's atmosphere therefore presents a strong pressure gradient that drives a tangential flow from the warm, high pressure towards the cold, low pressure regions, in a surface boundary layer. It reverses direction during the day and is maximal at sunrise and sunset, with a shear velocity u_* on the order of a fraction of the thermal velocity.

Threshold for grain motion: The vapor density in the coma is orders of magnitude lower than that of air on Earth. The threshold shear velocity u_t above which sediments are transported by a wind is quantitatively determined by the balance between gravity, hydrodynamic drag and cohesive contact force. We find that, sufficiently close to perihelion, grains at the centimeter scale, such as those observed by Rosetta near the bedforms, can be transported by the afternoon thermal wind (Fig. 2). Importantly, this is only a small fraction of the time, around 15% of the comet's day. The asymmetry between sunrise and sunset winds, resulting from thermal inertia (some heat is stored in the superficial layer during the morning and released in the afternoon), has an important consequence: the morning wind is not strong enough to entrain grains.

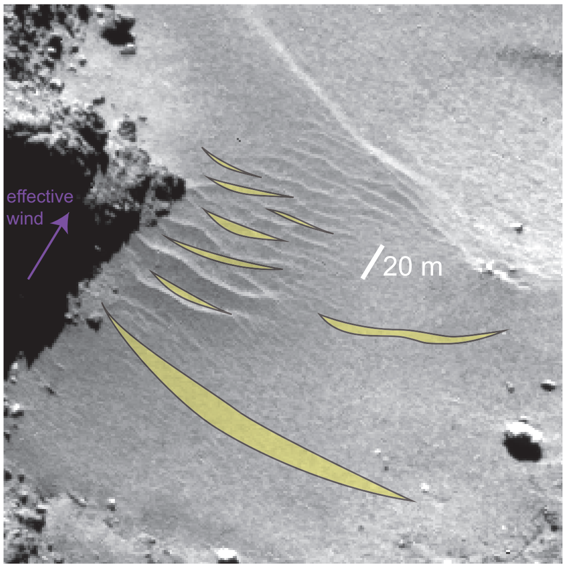

Fig 1: *View of the comet's bedforms in the neck (Hapi) region by OSIRIS narrow-angle camera dated 18 September 2014, i.e. before perihelion. Superimposed yellow marks: position of the ripples from a photo dated 17 January 2016, i.e. after perihelion providing evidence for their activity. Photo credits: ESA/Rosetta/MPS.*

Sediment transport: Given the very large density ratio between grains and vapor, the length needed to accelerate grains to the wind velocity is much larger than the comet size, meaning that the grains actually keep a velocity negligible in front of that of the wind. The moving grains are thus submitted to an almost constant drag force equal to that when the grains are static. We argue that the mode of sediment transport along the comet's surface is traction, where grains remain in contact with the substratum on which they roll or slide (Fig. 3). There are important differences with Earth that prevent a cometary saltation [4] in which the grains would move by bouncing or hopping. The flow is turbulent above a viscous sub-layer, typically 0.7 m thick at perihelion, where turbulent fluctuations are damped by viscosity. After a rebound, grains with enough energy to reach the turbulent zone would be entrained into suspension, since the settling velocity is much smaller than turbulent fluctuations. These grains would acquire a vertical velocity larger than the escape velocity, on the order of a meter per second, and would eventually be ejected into the coma.

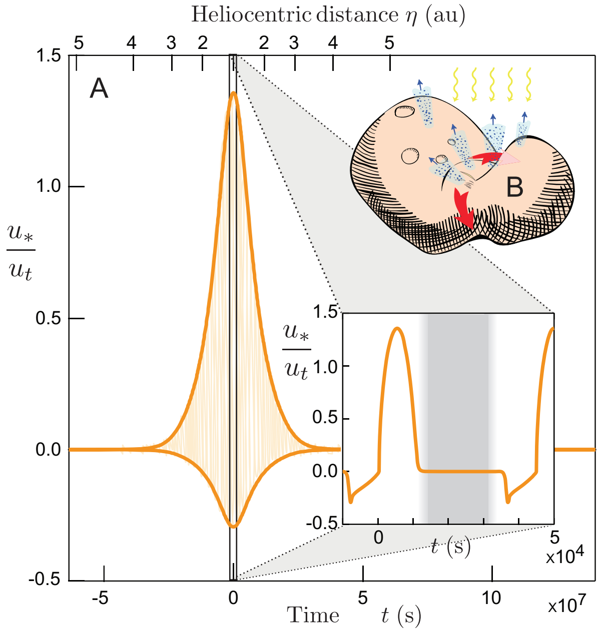

Fig 2: **A** *Time evolution of the velocity ratio u_*/u_t calculated along the comet's orbit around the sun. Time is counted with respect to the zenith, at perihelion. Bold orange lines: envelopes of the daily variations (inset), emphasizing* the *maximum and minimum values. Inset: Zoom of the evolution of u_*/u_t during one comet day, at perihelion. The day/night alternation is suggested by the background grey scale. Wind is above the transport threshold in the afternoon (counted positive) and in the morning (negative).* **B** *Schematic of the outgassing (blue) and the resulting winds (red arrows) driven by pressure gradients from illuminated to shadow areas.*

Bedforms: Aeolian dunes and subaqueous ripples form by the same linear instability, which is now well modeled and quantitatively tested against laboratory measurements. The destabilizing effect results from the phase advance of the wind velocity just above the surface with respect to the elevation profile. The stabilizing mechanism comes from the space lag between sediment transport and wind velocity. It is characterized by the saturation length L_{sat} defined as the sediment flux relaxation length towards equilibrium [3,5,6]. As all other parameters are known, L_{sat} is the key quantity selecting the most unstable wavelength λ. Applying linear stability analysis for 67P, we compute this wavelength, and empirically find that it approximatively scales as $\lambda \sim L_{sat}^{3/5}(\nu/u_*)^{2/5}$. We use here the analogy with subaqueous bedload, for which controlled experiments on emerging subaqueous ripples allow us to deduce $L_{sat}=24d$ and retain this law for traction on the comet. The mean grain diameter d observed at the surface of the comet in the Ma'at region is in the range 10-40 mm. The model correspondingly predicts an emergent wavelength between 10 and 20 m, in good agreement with the observed crest-to-crest distance. For such grains, the traction sediment flux is computed on the order of 4. 10^{-5} m^2/s. The corresponding ripple growth time is 5. 10^4 s. For comparison, the total time during which sediment transport takes place during a revolution around the sun, which is around 10^6 s, is 20 times larger. The ripples therefore have enough time to emerge and mature during one comet revolution.

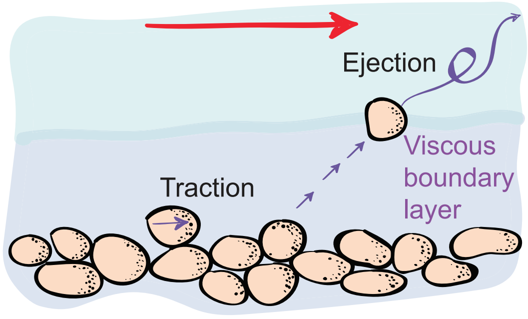

Fig 3: *Schematic of the vapor flow (red arrow) above the granular bed. Grains rebounding on the bed can reach the upper turbulent zone and are eventually ejected in the coma, which prevents the existence of saltation. The only mode of sediment transport along the bed is traction. Violet background: viscous sub-layer close to the bed, typically $10\nu/u_*=0.7$ m thick close to perihelion.*

Conclusion: Although generated by a rarefied atmosphere, these bedforms are therefore analogous to ripples emerging on granular beds submitted to viscous shear flows. The analog of aeolian dunes would have an emergent wavelength of 10^8 m due to the extremely large density ratio on the comet [5,6], i.e. much larger than the comet itself. Similarly, using the comet's values, the analogue for aeolian ripples would produce a pattern of wavelength 10^4 m [7]. The quantitative agreement we can reach here shows that our understanding of the coupling between hydrodynamics and sediment transport is able to account for bedform emergence in extreme conditions and provides a reliable tool to predict the erosion and accretion processes controlling the evolution of small solar system bodies. This abstract is a summary of [8], where more details, as well as a proper bibliography, can be found.

References: [1] Thomas N. et al. (2015) *Science* 347, aaa0440. [2] Charru F., Andreotti B., Claudin P. (2013) *Ann. Rev. Fluid Mech.* 45, 469-493. [3] Sierks H. et al. (2015) *Science* 347, aaa1044. [4] Thomas N. et al (2015) *AA* 583, A17. [5] Claudin P., Andreotti B. (2006) *EPSL*, 252, 30-44. [6] Durán O., Claudin P., Andreotti B. (2011) *Aeolian Res.*, 3, 243-270. [7] Durán O., Claudin P., Andreotti B. (2014) *PNAS* 111, 15665-15668. [8] Jia P., Andreotti B., Claudin P. (2017) *PNAS* 114, 2509-2514.