GAS OF DUST PARTICLES: A POSSIBLE MECHANISM OF AEOLIAN FEATURES FORMATION ON KILOMETER-SIZE BODIES.

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Introduction: Images of comet 67P/Churyumov-Gerasimenko nucleus obtained by Rosetta mission show a number of morphological features strongly resembling aeolian features on the Earth and Mars [1,2]. They include wind tails of boulders, longitudinal striations in smooth apparently loose material, and, most conspicuous, a patch of ripples in Hapi region. The major ripples have spacing of ~12 m and height of a few decimeters [1]; smaller ripples have ~5 m spacing.

The presence of such features is puzzling, because the comet obviously lacks any "normal" atmosphere and winds. However, the comet nucleus does produce gas due to its activity (sublimation of volatile ices: CO_2, CO, N_2, etc.), and a number of authors attributed aeolian-like features to this gas. Before the ripples on 67P were discovered, A. Cheng et al. [3] had analyzed morphology of three other, imaged at a worse resolution comets (103P/Hartley 2, 81P/Wild 2, 9P/Tempel 1) and suggested a role of particles lifted by gas flow in formation of morphological features. They had estimated that the outgassing is sufficient for lifting sand-size and larger particles. They had noted that, because of the divergent gas flow geometry, "classic" saltation and, therefore, formation of the "classic" aeolian bedforms is unlikely. Several later works [e.g., 4-6] have argued for saltation or reptation in the comet environment, however, those treatments have caveats. The molecule free path in cometary gas jets is much longer than sand particle size ($Kn \gg 1$), therefore aerodynamic treatment of gas flow interaction with particles is not applicable; corrections for non-zero Kn considered in [6] are only valid for weakly rarefied gases ($Kn \sim 1$); the treatment in [6] also ignores the essentially divergent nature of the gas flow on comets. If dust particles are entrained into gas jets, they are likely to get velocities above the escape velocity, and therefore would mostly escape rather than produce bedforms [1].

N. Thomas et al. [1] suggested that the "aeolian" features are produced by fall of relatively large particles lifted with low velocities by gas. I was able to reproduce the observed boulder-related ventifacts with a simple cellular-automata-type model of erosion by falling particles [7], but fail to produce anything resembling ripples with such kind of modeling.

Here I propose a principally different mechanism potentially capable of formation of aeolian features on low-gravity bodies.

Gas of dust particles on low-gravity bodies: Free dust particles on a low-gravity body would fly and form a specific dust atmosphere due to their thermal motion. Below I present order of magnitude estimates for such an atmosphere assuming conditions for Hapi region of 67P: gravity $g = 10^{-4}$ m s^{-1}, and temperature $T = 200$ K, which corresponds to a dark low-thermal-inertia surface under direct sunlight with 60° incidence angle at 3 AU from the Sun (these illumination conditions are typical for Hapi region). Dust particles are assumed to have diameter $d = 0.5\ \mu$ (typical dust in cometary coma) and material density of $\rho = 1$ g cm^{-3}.

In the thermal equilibrium, dust particle has a thermal energy of $\frac{1}{2}kT$ per degree of freedom, where k is the Boltzmann constant. The "atmosphere" of such particles has a scale height $H = kT / mg \sim 4$ m, where m is particle mass defined by d and ρ. In the terrestrial conditions, such an atmosphere is not forming, because under terrestrial gravity $H \ll d$ for any d. The dust atmosphere is forming only when $H > d$, that is particles are sufficiently small: $d < (kT / \rho g)^{1/4} \sim 10\ \mu$. The typical particle velocity is $c = (kT / m)^{1/2} \sim 6$ mm/s, and the thermal spin rate is ~0.5 c / d ~ 6000 rotations per second.

If the gas of dust particles is rarefied, its density $\rho_g \ll \rho$, many properties of such gas are the same as of an ideal gas. The speed of sound is equal to $c \sim 6$ mm/s. The adiabatic lapse rate is zero. Specific heat is defined by heat capacity of dust particles (kinetic energy of thermal motion and spin is negligible in comparison to the internal energy of the particles). Viscosity, if calculated as for an ideal gas, $0.09(\rho kT/d)^{1/2} \sim 2\times10^{-7}$ Pa s is extremely low, however, correct viscosity calculation should take the restitution coefficient (non-elastic particle collisions) into account. The latter is also true for all thermal conductivity and diffusion coefficients.

If the dust particles at the surface are abundant, the gas density next to the surface is $\rho_g \sim 0.5\rho \exp(-E/kT)$, where E is the characteristic bound energy of a dust particle, which is very poorly defined. Even if the particles are "loose" and "free", they are bound to each other with van der Waals forces. Energy of van der Waals interaction of two spheres of diameter d is usually parameterized following Hamaker's theory as $E \sim (1/24)A\ d/l$, where A is the Hamaker constant on the order of $\sim10^{-21} - 10^{-19}$ J, which depends on particle material, and l is on the order of a few atomic distances (>0.1 nm) and depends on "clearness" of the particle surface: the presence of adsorbed volatiles, nano-scale surface irregularities, etc. Typical values for freshly grounded rocks, lunar regolith, etc. ($A \sim 10^{-20}$ J,

$l \sim 0.4$ nm, [8]) give $E/kT \sim 70$, and no dust atmosphere would exist. Organic material of cometary dust may have a lower A, and due to adsorbed volatiles l might be greater; diversity of individual particle properties may lead to a gentler dependence than $\exp(-E/kT)$. These factors together may give a way for some dust atmosphere, at least for smaller, submicron particles. On the other hand, particle deformation at the contact is ignored by Hamaker's theory, but might be significant for soft organic particles, which would make them much more cohesive (increase E) and thus preclude formation of the dust atmosphere. I assume for a while that ρ_g is not negligible.

Pressure at the surface is $P = \rho_g gH$. The maximum possible pressure (if $E << kT$) is $0.5\rho gH \sim 0.02$ Pa. Geometric optical depth of the atmosphere $\tau = 1.5(\rho_g/\rho)(H/d)$. Optical depth is $\sim 2\tau$ for short wavelength λ, and $\sim 6\tau(d/\lambda)^4$ for long wavelength. Radiative time scale of a thin dust atmosphere is ~ 1 s and does not depend on d for micron-scale and smaller particles. Real dust atmosphere would consist of a range of particle sizes, each with its own H, which would produce strong stratification in the atmosphere. Winds in the dust atmosphere can be generated by thermal tides. Formation of dust atmosphere on tilted surfaces would lead to supersonic downhill flow.

The mean free path in a thin ($\rho_g/\rho << 1$) atmosphere is $\sim 0.1(\rho/\rho_g)\, d$. For sand-size particles $Kn >> 1$, and the classic theory of saltation initiation is not applicable. It is obvious, however, that particles slightly larger than the typical atmosphere-forming dust may be mobilized and transported by reptation. The mean free path is always much shorter than the incipient bedform spacing, which is also proportional to (ρ/ρ_g) according to Claudin & Andreotti [9]. This means that the fluid dynamic-based theory of the incipient bedform spacing is applicable to the dust atmosphere. In a sense, transport by the dust atmosphere is more resembling sub-aqueous rather than sub-aerial transport: the range of saltation particle size between suspension and reptation is narrow, the upper boundary of the atmosphere is close to the surface and may affect bedform formation, similarly to shallow water.

Application to 67P: Hapi region with the ripple patch coincides with the area of the lowest gravitational potential (corrected for the centrifugal potential) [10] on the nucleus. Its "watershed" comprises over a half of the nucleus area. The region has the highest albedo and the lowest red spectral slope on the nucleus, which is consistent with higher concentration of fine dust in comparison to the other regions. This suggests global transport of fine dust downslope, which would be a straightforward consequence of formation of dust atmosphere. Striations on loose material on slopes and boulder-associated ventifact-looking features might result from (supersonic) flow of dust gas downslope.

The ripple patch is not located at the lowest portion of the Hapi basin: a slope of ~10° is reported in [1], however, the gravity model based on assumption of homogeneous nucleus material might be inaccurate.

If the smallest observed ripples are incipient bedforms following Claudin & Andreotti [9] scaling, and they are formed by 10 μ (1 mm) particles, the required atmosphere density is $\rho_g \sim 10^{-4}\rho$ ($10^{-6}\rho$), and corresponding $\tau \sim 150$ (1.5). This means that such a dust atmosphere, if existed, would be opaque and readily seen in the available images, but it actually is not observed. This might mean that the dust atmosphere has never formed (because of cohesion), and the ripple formation mechanism is different. It is also possible that the dust atmosphere is optically thin, it (slowly) form ripples, but they do not follow the scaling law due to some peculiarities of the diluted gas of dust particles. Alternatively, it is possible that the ripples are relic from a past epoch, where a dense dust atmosphere was forming. Later much atmosphere-forming dust might be blown away by outgassing (which indeed was observed in Hapi region) or might stuck to the surface (significantly increased E) due to diffusion. There might be a seasonal cycle of accumulation and removal of fine dust in Hapi, and Rosetta might arrive too late to see a dense dust atmosphere.

Application to other bodies: Formation of dust atmosphere and related geomorphic features is possible for bodies in some size range. For bodies smaller than ~100 m, the scale height exceeds the body radius, and the extended dust atmosphere would escape. For bodies larger than ~100 km, H is too short, and no real atmosphere is forming, while thermal-induced dust mobility might play some role up to ~1000 km bodies. Comets are probably better for dust gas than asteroids because of presumably lower cohesion. Higher surface temperatures favor dust atmospheres.

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