ADHESION FORCES BETWEEN REGOLITH PARTICLES: CONSTRAINTS ON THE CONDITIONS OF ELECTROSTATIC LOFTING OF DUST. L. V. Starukhina, Astronomical Institute of Kharkov University, 35 Sumskaya St., Kharkov, 61022, Ukraine, starukhina@astron.kharkov.ua

Introduction: Sunlight scattering on electrostatically lofted fine dust is considered to produce the horizon glow observed at the lunar terminators during the Apollo expeditions [1]. At the dayside of the Moon, regolith surface becomes positively charged due to photoelectron emission; at the nightside, the charge is negative due to electrons of the solar wind. Particle detachment from the surface under the action of a force of still unknown nature (e.g., seismic or electrostatic) may be the key to understanding of the origin of the ponded deposits on Eros [2]. In most theories of dust lofting developed so far, repulsion of regolith particles from the surface was compared with gravitational attraction of the particles to the parent body, so gravity was supposed to be the only or the main obstacle that prevents particle lofting. This is valid in particle flight, but not at the moment of the start. In the approach of gravity-controlled detachment, limitations on the size of lofting particles are rather weak. E. g., at surface potentials of a few volts, gravity force becomes negligible as compared to the electrical force at sizes ≤ 10 μm.

Much stronger restrictions are imposed on the lofting conditions by the adhesion forces that act until the moment of particle detachment from the surface. The forces are often underestimated, being mixed up with cohesion that is really small enough to be neglected [3]. However, cohesion is an integral property of a soil as an assemblage of thousands of particles, so it does not characterize individual contacts between particles of different shapes and sizes. At the moment of particle start, two individual particles are involved and not a soil as a whole. Therefore, the sticking force that acts upon an individual particle is appropriate.

The importance of adhesion in particle lofting was stressed in [4], but the formulas for the interparticle adhesive forces were not derived, which did not enable the authors to explicitly formulate the restrictions on particle detachment. In the present work, we consider these restrictions in detail applying the characteristics of interparticle contact obtained in [5].

Forces in contact between regolith particles: Capillary force that sticks together two particles of local curvature radius r in the contact zone is

$$F_c = 2\pi r\Delta\alpha. \qquad (1)$$

Here $\Delta\alpha = \alpha_1+\alpha_2-\alpha_{12} \sim 10^2\text{-}10^3 \text{erg}\cdot\text{sm}^{-2}$ is the difference between specific surface energies α_1, α_2 of adjacent particles and specific surface energy α_{12} of the boundary between them. For smooth particles of regular shape (not disk- or needle-like), the local curvature radius r in the contact zone is close to the half of the particle size l. For rough particles, the radius r can be much smaller. Typical local radii $r \sim 1\text{–}10$ μm. The lower limit for the local radii r is determined by smoothing processes, that can occur by different mechanisms of mass transfer, e. g., surface and volume diffusion, plastic and viscous flow. For curvatures of submicron radii, smoothing time is rather short; e. g., in case of surface diffusion it is proportional to r^4 and for $r \le 0.1$ μm may be from hours to 10^4 years [5]. Therefore submicron particles cannot be expected to be too rough and their local curvature is close to the particle radius.

The force (1) acts from the initial moment of particle contact. For large duration of a contact between two particles, (~10^4 years), stronger sticking can develop due to mass transfer of material in the contact zone. In case of plastic flow [5]:

$$F_p = 2\pi r\Delta\alpha(\sigma_s/\sigma_p). \qquad (2)$$

Here σ_s and σ_p are limits of strength and plasticity, respectively, $\sigma_s/\sigma_p \sim 10^2$.

Comparison of sticking to gravity shows that dust particles are attached to regolith surface mainly by sticking forces, attachment by gravity being negligible for soil particles < ~1mm at the lunar surface and up to tens of cm on most asteroids [5].

Experimental testing of the formulae for interparticle sticking forces. Formulae for the area of interparticle contact and, consequently, for the sticking forces (1), (2) were tested in [5] by comparison of the macroscopic characteristics of lunar regolith derived from (1) and (2) with the measured values. The comparison showed that strong "plastic" contact is more typical. Direct measurements of interparticle sticking forces [5] confirmed this conclusion. However, since rather small portion of regolith takes part in electrostatic levitation, for estimation of particle detachment conditions we will use the formula (1) for weaker capillary contact.

Comparison of the sticking and electrical forces: Electrostatic repulsion force of a particle of a radius r from a substrate, both charged at potential φ, is

$$F_q = q^2/r^2 = \varphi^2 \quad \text{(CGS), or}$$
$$F_q = q^2/4\pi\varepsilon_0 r^2 = 4\pi\varepsilon_0\varphi^2 \quad \text{(SI)}, \qquad (3)$$

where ε_0 is dielectric constant for vacuum in SI. Comparison with (1) shows that, to overcome interparticle sticking, particle radius

$$r < r_{cr} = 2\varepsilon_0\varphi^2/\Delta\alpha \quad \text{(SI)} \qquad (4)$$

is required. At typical values of $\Delta\alpha \sim 100$ erg/cm^2 ~ 0.1 J/m^2 and surface potentials φ of a few volts, this gives the critical radius of the order of interatomic distances, i.e., too small to describe any real particle. Thus, at the dayside potentials of a few volts, particle charges are insufficient to overcome typical sticking forces. At potentials of a few tens of volts, only particles of $2r <$ ~0.2 microns can be torn off the surface. Particles of larger sizes can be detached either due to the submicron roughness of their surfaces or due to extremely small difference $\Delta\alpha$ in specific surface energies. Such particles make up very loosely bound regolith component and could be mostly lost in lunar soil transportation by Apollo expeditions.

Eq. (4) can be also considered as a restriction for surface potentials, if the radii of levitating particles are supposed to be known. Thus, at $r_{cr} = 5$ μm (as estimated in [1]), the potential required for detachment is ~400 volts.

Conclusions:

(1) Sticking forces between regolith particles are the main obstacle for particle detachment from the surface under applied external force, in particular, in electric fields due to emission of photoelectrons at solar irradiation and solar wind plasma interactions. Low upper limit of the size of particles that can be torn off the surface by such fields may explain the failure of experimental attempts to observe any particle motion even with intense ultraviolet light [7].

(2) The charged dust particles that can be ejected from the dayside of the Moon should have extremely low adhesion to the adjacent regolith particles. At typical specific surface energies and dayside surface potential of a few volts, regolith particles cannot overcome sticking forces. At potentials of a few tens of volts, only particles less than ~0.1 microns can be torn off the surface. For electrostatic levitation of ~5 μm particles, surface potential of a few hundreds of volts is required.

(3) Higher nightside potentials result in wider range of sizes of particles flying off from the nightside as compared to the dayside of the Moon, which can result in higher density of dust in nightside of the lunar exosphere.

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References: [1] Criswell D. R. (1973) *Photon and Particle Interaction with Surfaces in Space*, D.Reidel Publishing Co., Dordrecht, 545-556. [2] Robinson M. S. et al. (2001) Nature 413, 396-400. [3] Rhee J. W. et al. (1977) *COSPAR Space Res. XVII*, 627-629. [4] Pelizzari A. and D. R. Criswell (1978) *Proc. LPSC 9th*, 3225-3237. [5] Starukhina L. V. (2000) *Solar System Res. 34*, 295-302. [6] Arrhenius G. and S. K. Asunmaa (1973) *The Moon 8*, 368-391. [7] Gold T. and G. J. Williams (1973) *Photon and Particle Interaction with Surfaces in Space*, D.Reidel Publishing Co., Dordrecht, 557-560.