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ScienceDirect

Advances in Space Research 58 (2016) 560–563

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Lunar nanodust: Is it a borderland between powder and gas?

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Received 30 November 2015; received in revised form 1 April 2016; accepted 13 May 2016
Available online 20 May 2016

Abstract

There is still no clear understanding of the mechanism responsible for two lunar dust peculiarities. Firstly, tenuous clouds of dust grains amazingly soar at an altitude of about a meter above the sunlit surface. Secondly, lunar dust has a powerful devastating effect on various materials. Here, we show that thermal fluctuations may be both the cause of the low-altitude levitation and the main "damaging factor" of lunar dust. Indeed, fine particles should soar above hot surface and the presence of nanoparticles with enormously varying mass values provides the most efficient use of thermal energy to break bonds between nanoscopic structural elements of target material. These features must be intrinsic to any nanoparticle assemblies in the absence of large conglomerates that are sure to arise in terrestrial conditions.

Keywords: Lunar dust; Dust levitation; Thermal fluctuations; Adhesion; Damage effect

1. Introduction

There is strong evidence that fine particles of lunar dust are lifted from the lunar surface. This effect was observed by cameras onboard the NASA's Surveyor landers (Rennilson and Criswell, 1974) as a line of light along its western horizon following local sunset. The similar effect was observed by astronauts of several Apollo missions (Zook and McCoy, 1991). Search for the lunar horizon glow was conducted using data returned from the Lunar Reconnaissance Orbiter camera (Stubbs et al., 2016). It has been suggested that this horizon-glow (HG) is sunlight, which is forward scattered by dust grains present in a tenuous cloud formed temporarily just above sharp sunlight/shadow boundaries in the terminator zone. Electrically charged grains could be levitated into the cloud by intense electrostatic fields (>500 V cm^{-1}) extending across the sunlight/shadow boundaries. Detailed analysis of the HG absolute luminance, temporal decay, and morphology confirm the cloud model. The observations by the NASA's Surveyor landers (Rennilson and Criswell, 1974) are in qualitative agreement with the electrostatic levitation model (Criswell, 1973). In this model the authors proceeded from the assumption that the dust grains on the lunar surface are electrically charged by interaction of the local plasma environment with the Moon and by the photoemission of electrons from the lit lunar surface. This effect causes the charge of the dust grains, their levitation over the surface and create a near-surface electric field. This levitation mechanism must eject 10^7 more particles per unit time into the cloud than could eject micro meteorites. The authors of the paper (Rennilson and Criswell, 1974) emphasize that electrostatic transport is probably the dominant local transport mechanism of lunar surface fines. Without questioning this model in this paper we will show that thermal fluctuations can create a similar flow in the presence of rather fine particles. Besides, we considered

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http://dx.doi.org/10.1016/j.asr.2016.05.022

possible causative connection of dynamics of dust nanograins with the destructive effects of lunar dust.

2. Thermal fluctuations and low-altitude dust levitation

The classical molecular-kinetic theory does not make any distinctions between small particles and molecules of gas behavior. As it follows from the classical theory (Landau and Lifshitz, 1980) in ensemble of any particles, the average square of fluctuation of any component of the particle velocity is inversely proportional to its mass m and proportional to the absolute temperature of the ensemble T

$$\langle v_i^2 \rangle = k_B T/m. \tag{1}$$

Supposing that the dust grains that are located on the Moon surface lit by sun do not stick together and have the temperature $T \approx 400$ K (Vaniman et al., 1991), we obtain that the average value of fluctuation of the vertical component of velocity is equal to

$$v_\perp \approx \sqrt{6\frac{10^{-21}}{m}} \approx 2\frac{10^{-12}}{d_{eff}^{3/2}}\ \mathrm{m\,s^{-1}}. \tag{2}$$

The last equality is obtained under the assumption that the shape of the particles is close to spherical with an effective diameter d_{eff} (expressed in meters), the density of the lunar soil is taken (Vaniman et al., 1991) equal to $\rho \approx 3 \times 10^3\ \mathrm{kg\,m^{-3}}$.

With the initial velocity (2) a dust grain can levitate at an altitude

$$h \approx \frac{k_B T}{\rho g d_{eff}^3} \approx \frac{10^{-24}}{d_{eff}^3}\ \mathrm{m} \tag{3}$$

($g \approx 1.6\ \mathrm{m\,s^{-2}}$ is the free-fall acceleration on the Moon surface). For the dust grains with a diameter of 100 nm, Eq. gives the velocity of several centimeters per second, so (3) is equal only to about a millimeter. Although particles of such size virtually do not levitate over the surface, their chaotic motion has to result in their "stir" or "boil" effect in the upper layer and a decrease in its density. The situation sharply changes with decreasing size, and dust grains with a diameter of the order of 10 nm already have the thermal velocity sufficient for levitation at an altitude of about a meter for several seconds.

Therefore, one can expect that if cohesive forces between the dust nanograins are rather weak, then above the surface areas of the Moon that are lit by the Sun (and, hence, hot) there must arise a layer of nanosized dust grains levitating due to thermal motion. According to Eq. (3), the thickness of this layer can be on the order of a meter, and the density of dust in it should change with altitude in accordance with the standard barometric formula.

Certainly, the intensity of Raleigh scattering of light, which is proportional to the sixth power of size, by such small dust grains is quite low. However, it should be taken into account that in fact the shape of dust grains is quite intricate (Liu et al., 2008), so that their real linear dimensions can significantly differ from d_{eff}. Besides, the intensity of light scattering by a dust cloud is proportional to its density. Therefore, the intensity of the low-altitude horizon glow will be higher, (i) the thicker the surface layer from which the dust is thrown upward and (ii) the higher the concentration of superfine particles are in this layer.

In compliance with different data, see e.g. (Park et al., 2008) and the references therein, in several samples, the mass of dust grains with a diameter of up 1 μm made up a few percent the total dust mass, with the amount of dust grains with a size of up to 100 nm being from 25% to 40% the whole amount of the dust grains. Finally, note that the mechanism of thermal fluctuations provides levitation of virtually all sufficiently small (about a few tens of nanometer) particles from the upper dust layer. In this relation, the efficiency of the electrostatic mechanism, which is commonly employed for the explanation of the dust levitation (Criswell, 1973; Stubbs et al., 2006), is incomparably lower.

3. Thermal fluctuations and destructive effect of the dust

Now, we discuss a possible mechanism of the damaging influence of the lunar dust on the equipment and materials (Linnarsson et al., 2012). "Over the course of six Apollo missions, not one rock box maintained its vacuum seal," wrote Harrison Schmitt, an Apollo 17 astronaut (Schmitt, 2006). Certainly, the thermal energy of a single atom $3k_BT/2$, and hence, average kinetic energy of a fine dust grain are quite low. However, regarding the damaging efficiency, not only the energy quantity but what it is particularly spent on is extremely important. In other words, to destroy an object, powerful blows are by no means always necessary – commonly, a point hit is sufficient.

If the target to be hit consists of relatively weakly assembled fragments inside which atoms are strongly bound to each other (polymer chains, fine-grain polycrystals, etc.), the threshold energy of damaging is the bond energy per individual fragment. Consequently, for a more effective usage of the kinetic energy of the incident dust grain, its mass should approximately coincide with the mass of the fragment knocked off the target.

If the mass of the dust grain is much less, it would bounce, preserving its kinetic energy. If it is much higher, the number of the target fragments among which the energy is distributed increases. Only when the masses coincide, the grain (in case of central blow) would stop and the object being hit would acquire all its energy and impulse. An obvious case is hitting a brick wall by bodies of different masses. A standard bullet having the kinetic energy of about 2.5 kJ would ricochet from the wall having made only a small pit. However, a blow of 10 kg- sledge dropped from an altitude of 25 m (or 50 kg-hammer, from 5 m) can already be far more destructive. In case of the lunar dust, we deal with a lot of "bullets", "sledges", and "hammers",