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Shaking as means to detach adhered regolith for manned Phobos exploration

Christine M. Hartzell[a,*,1], William Farrell[b,2], John Marshall[c,3]

[a] University of Maryland, 3178 Martin Hall, College Park, MD 20742, USA
[b] NASA/GSFC, Mail Code: 695, Greenbelt, MD 20771, USA
[c] SETI Institute, 189 N Bernardo Ave #200, Mountain View, CA 94043, USA

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Abstract

Recent work has shown that cohesion drives the behavior of surficial regolith grains up to centimeters in size on the surface of small planetary bodies such as asteroids. Mars' moon Phobos is similar in morphology and size to asteroids. Additionally, Phobos has been discussed as a possible target for human exploration, due to its relatively small gravity well. Dust adhering to spacesuits (and subsequently detaching in a pressurized spacecraft) was a source of concern during the Apollo era. We apply improved understanding of the forces active on regolith grains to compare their relative strength, showing that Phobian regolith up to millimeters in size is likely to be dominated by Van der Waals cohesion. Additionally, we show that astronauts will be unable to detach dust grains smaller than 1–100 μm that are adhered to their gloves through shaking alone, with the size range for detachment depending on the material properties of the regolith and spacesuit.

Keywords: Phobos; Regolith; Cohesion

1. Introduction

Due to the low gravity on asteroids (three to five orders of magnitude smaller than that of the Moon), Scheeres et al. (2010) have recently shown that van der Waals cohesion dominates the behavior of asteroid regolith. Van der Waals cohesion is caused by the polarization of neutral molecules. Cohesion causes the clumping commonly observed in fine terrestrial powders (such as baking flour). Due to the reduced gravitational acceleration on small planetary bodies, however, regolith grains up to centimeters in size can exhibit the same cohesive powder characteristics that are observed in micron-scale powders on Earth.

Additionally, the weak surface gravity on small bodies has also reignited interest in the significance of electrostatic forces caused by the interaction of charged regolith with the local plasma environment (Hartzell et al., 2013; Hartzell and Scheeres, 2011; Hughes et al., 2008; Criswell and De, 1977). The surface of airless bodies interacts directly with the solar wind plasma and solar UV radiation. As a result, the surface regolith grains develop a non-zero charge (Colwell et al., 2007). Generally, grains are predicted to be positively charged during the day and negatively charged at night, although recent work has shown the significance of grain-level interactions with the plasma environment (Zimmerman et al., 2016; Wang et al., 2016). The positively charged sunlit surface attracts electrons from the solar wind plasma, producing a region with

* Corresponding author.
E-mail addresses: hartzell@umd.edu (C.M. Hartzell), William.M.Farrell@nasa.gov (W. Farrell), jmarshall@seti.org (J. Marshall).
[1] Department of Aerospace Engineering, University of Maryland.
[2] NASA Goddard Spaceflight Center.
[3] SETI Institute.

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increased electron density called the plasma sheath. A wake region forms downstream of the body, as a large electric field is required to accelerate the heavy ions perpendicular to the freestream direction (Zimmerman et al., 2014). The interaction of the charged dust grains with the local electric field in the plasma sheath will produce an electrostatic force. Interactions between charged dust grains may also produce dust motion (Zimmerman et al., 2016).

Phobos has recently been considered as an intermediate destination for human missions on the path to Mars (Price et al., 2015). Phobos provides a venue to test technologies required for a successful Mars mission (namely, long duration human spaceflight). Additionally, Phobos lacks a significant atmosphere and has a relatively small mass. These two characteristics significantly simplify landings on Phobos as compared to Mars, which requires significant development in entry system technology to successfully land a human mission.

Lunar dust strongly adhered to astronaut spacesuits during the Apollo missions (Christoffersen et al., 2008). The adhered dust is clearly visible in images of the astronauts on the lunar surface as well as in modern-day inspections of the returned spacesuits (Christoffersen et al., 2008). However, some portion of the dust that adhered to the spacesuits was released when the spacesuits were removed in the pressurized environment of the Lunar Module (Phillips, 2006), causing concerns about the health effects of inhaling lunar regolith.

Since Apollo, our understanding of the forces that dominate regolith behavior has expanded considerably. In the following sections, we will describe the forces active in the regolith of Phobos and evaluate the ability of future astronauts to remove dust from their spacesuits through vibration, neglecting any mechanical adhesion of the regolith to the fabric. This analysis will inform the design of future manned missions to Phobos.

2. Force models

Our goal is to model the relative strength of forces acting on regolith grains in contact with an astronaut's glove and evaluate the ability of the astronaut to detach grains from his/her glove. We assume that the astronaut is standing at Phobos' equator. The forces acting on the dust grains are: gravity, cohesion, and the electrostatic force and centripetal acceleration. Fig. 1 shows the general reference frame used.

We assume that $\hat{a}_3$ is normal to the surface and aligned with the astronaut's body. In our evaluation of the detachment of dust grains from an astronaut's glove, we assume that the glove is held perpendicular to the local gravity vector and assume a spherical gravity field. The dust grain may be on the palm or top side of the glove. In order to evaluate if a dust grain will detach from an astronaut's glove, we must calculate the acceleration of the dust grain with respect to the astronaut's glove. Considering a grain attached to a glove, the grain has zero velocity with respect

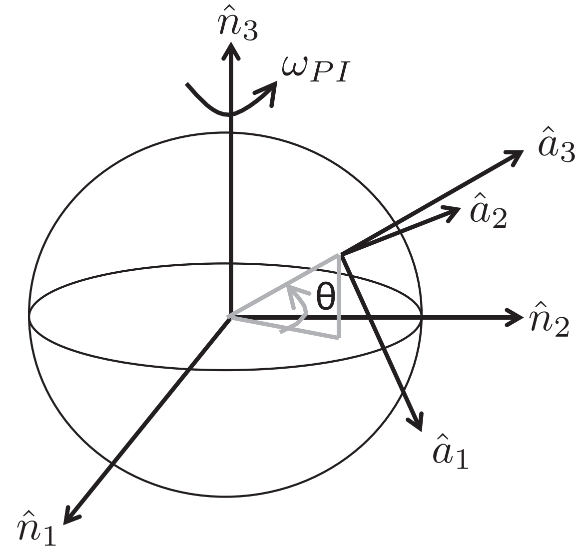

Fig. 1. Coordinate systems used. $\hat{n}_i$ indicates the inertial frame and $\hat{a}_i$ indicates the astronaut frame, where $\hat{a}_3$ is normal to the surface.

to the glove until it experiences some non-zero acceleration (in the glove frame) to detach it from the glove. This can be intuitively understood if the glove is motionless (imagine a grain falling from the 'bottom' of a glove). We define the position of the dust grain to be:

$$\vec{r} = (R_p + h)\hat{a}_3 + \vec{g} \quad (1)$$

where R_P is the radius of Phobos (assumed to be 11.2667 km) and h is the height of the dust grain (astronaut hand) above surface. $\vec{g}$ is the vector from the nominal astronaut hand location to the grain. Later, we will assume that the astronaut can shake his/her hand vertically, which will describe the time variation of $\vec{g}$. The transport theorem gives us that the inertial acceleration of the dust grain is:

$$\frac{{}^I d^2\vec{r}}{dt^2} = \frac{{}^A d^2\vec{r}}{dt^2} + 2\vec{\omega}_{PI} \times \frac{{}^A d\vec{r}}{dt} + \vec{\omega}_{PI} \times \left(\vec{\omega}_{PI} \times \vec{r}\right) \quad (2)$$

where $\vec{\omega}_{PI}$ is the rotation of rate of the astronaut frame (which is fixed to the surface of Phobos) with respect to the inertial frame. Thus, ω_{PI} is the rotation rate of Phobos with respect to the inertial frame and is assumed to be entirely about the $\hat{n}_3$ axis with a period of 27,540 s. Note that Eq. (2) gives the inertial acceleration of the grain (${}^I d^2\vec{r}/dt^2$) as a function of the acceleration in the astronaut frame (${}^A d^2\vec{r}/dt^2$), not the glove frame.

When calculating the ability of an astronaut to detach a grain from his/her glove (via shaking his/her glove), we approximate the astronaut's shaking motion as sinusoidal Eq. (3). Eq. (5) gives the acceleration of the glove:

$$\vec{g} = \delta h \sin(\lambda t)\hat{a}_3 \quad (3)$$

$$\frac{d\vec{g}}{dt} = \delta h \lambda \cos(\lambda t)\hat{a}_3 \quad (4)$$

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