Icarus 291 (2017) 65–74

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The effect of asymmetric surface topography on dust dynamics on airless bodies

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ARTICLE INFO

Article history:
Received 31 May 2016
Revised 22 November 2016
Accepted 17 March 2017
Available online 23 March 2017

Keywords:
Lunar dust
Horizon glow
Dust ponding
Lunar plasma environnment

ABSTRACT

Without a significant atmosphere or global magnetic field, the lunar surface is exposed to micrometeoroid bombardment, ultraviolet (UV) radiation, and the solar wind. Micrometeoroid bombardment grinds the surface into a regolith comprised of dust grains ranging in size from 10 nm to 1 mm (Grün et al., 2011). Incident UV radiation and solar wind electrons and ions electrically charge the surface forming a plasma sheath whose structure is dependent on both the plasma and surface properties (Campanell, 2013; Guernsey and Fu, 1970; Poppe and Horányi, 2010; Nitter et al., 1998). Dust grains that are liberated from the surface can collect additional charge and interact with the plasma sheath. These interactions have been suggested to explain a variety of phenomena observed on airless bodies including horizon glow and dust ponding (Colwell et al., 2005; Hughes et al., 2008; Poppe et al., 2012; Wang et al., 2009). The effect of surface topography on the plasma environment and ensuing dust dynamics is poorly understood and serves as the focus of this paper. We present the results of a three-dimensional particle-in-cell (PIC) code used to model the dayside near-surface lunar plasma environment at a variety of solar zenith angles (SZA) for two different topographies. Using the results of the PIC code, we model the effects on dust dynamics and bulk transport. The simulations also address dust transport on smaller bodies such as asteroid 433 Eros and comet 67P/Churyumov-Gerasimenko to identify effects of reduced gravity.

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1. Introduction

Open questions still remain about the role of topography and illumination effects on shaping the lunar plasma environment. This paper continues the work of Poppe et al. (2012), hereby referred to as P1, where dust transport was studied in the presence of a seven meter diameter crater on the lunar equator. In P1, the plasma environment was modeled with a 3-dimensional PIC code for varying solar zenith angles (SZA) and dust transport was modeled using the plasma densities and electric fields produced by the PIC code. P1 restricted dust dynamics to 2-dimensions and in summary reported the following results:

1. Electrostatically transported dust grains will tend to accumulate within crater boundaries as a result of the presence of complex electric fields near the crater edges.
2. Dust grains trapped within craters form a flat equilibrium spatial distribution within the crater.
3. The initial distribution of dust grains on the lunar surface does not impact the eventual equilibrium distribution of grains in the crater.
4. The crater traps larger grains at a higher efficiency than smaller grains due to the varying relative importance of the electrostatic and gravitational forces as a function of grain size.
5. The initial launch velocity of dust grains off of the lunar surface can significantly affect the trapping efficiency of craters.

We followed the same procedure as P1 but expanded the study of dust dynamics to 3 dimensions and included an asymmetric topography. The topographies considered were: (1) A simple crater with a diameter of 7 m and depth of 1 m (the focus of P1) and (2) the same crater with an additional 1 × 1 × 1 m block placed on the sunrise-side of the crater rim representing the presence of instrumentation, spacecraft, or a boulder. We assume the block to be an insulator with similar photoelectric properties as the lunar surface. Since surface charge is typically dominated by photoemission, the plasma environment and ensuing dust dynamics induced

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http://dx.doi.org/10.1016/j.icarus.2017.03.019
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by the block is dependent on the material only if the photoelectric or conductive properties are significantly different than that of the lunar surface. The second topography was chosen to study the effects of asymmetric topographies, near the scale of the plasma Debye length, and spacecraft. In Section 1 of this paper we overview the lunar dusty plasma environment. Section 2 describes the PIC simulations and dust model. Section 3 discusses the results and Section 4 finishes with a conclusion.

1.1. Near surface plasma environment

Throughout the lunar day, the near-surface lunar environment experiences a wide range of plasma and UV conditions conducive to a variety of sheath structures (Campanell, 2013, Nitter et al., 1998; Poppe et al., 2012). Near lunar dawn and dusk the photoemission of electrons due to UV radiation goes to zero allowing the solar wind to dominate surface charging. Due to the higher mobility of the solar wind electrons, as compared to the solar wind ions, the surface will charge negative resulting in a classical Debye sheath (Farrell et al., 2007; Halekas et al., 2008; Riemann, 1991). As the sun rises above the lunar horizon, the emission of photoelectrons increases. At maximum illumination (lunar noon), the photoemission current can be an order of magnitude higher than the solar wind currents (Feuerbacher et al., 1972) resulting in a positive surface charge density and a photoelectron sheath (Campanell, 2013, Guernsey and Fu, 1970; Nitter et al., 1998; Poppe and Horányi, 2010). Previous simulations have shown that under lunar conditions, at noon, a photoelectron sheath has a Debye length of $\sim$ 1 meter and a surface electric field strength of $\sim$ 5 V/m (Poppe and Horányi, 2010).

In addition to varying plasma conditions, topographic effects may play a major role in shaping the local plasma environment (Poppe et al., 2012). The low conductivity of the surface (Olhoeft et al., 1974; Borisov and Mall, 2006) combined with shadowing from topographic relief may create differential surface charging capable of producing stronger electric fields and induce bulk dust transport (Criswell and De, 1977; De and Criswell, 1977; Wang et al., 2007). Numerical models have suggested that differential surface charging in the terminator region can lead to large scale dust transport (Farrell et al., 2007). Understanding the role and influence of topography on dust dynamics in the near-surface environment may provide insight for future scientific missions as well as inform on hazard mitigation for engineering practices.

1.2. Lunar regolith characteristics and dynamics

Various observations of the lunar surface and other airless bodies have shown the presence of near-surface dust activity. The Apollo 17 Lunar Ejecta and Meteorite (LEAM) experiment observed the presence of slowly-moving highly charged dust grains in the near-surface region (Berg et al., 1974; Grün and Horányi, 2013). Images taken of horizon glow just after sunset by the Surveyor 5, 6, and 7 cameras have been interpreted as forward-scattered light off micron sized dust grains a meter off the surface (Rennilson and Criswell, 1974; Colwell et al., 2007). Observations from the NEAR spacecraft have exposed smooth dust ponds in the center of craters on 433 Eros comprised of micron sized dust grains (Robinson et al., 2001; Veverka et al., 2001; Cheng et al., 2002). Additionally, observations of Comet 67P/Churyumov–Gerasimenko (67P/CG), illustrate dynamic and variable dust processes present on the surface, including dunes, ripples, airfall, wind tails, and ponds (Thomas et al., 2015). In order to understand these phenomena and their extent, the dynamics and drivers of dust motion on airless bodies must first be understood.

Dust can be liberated from the surface via electrostatic forces (Flanagan and Goree, 2006), micrometeor impacts, instrument and human activity, or by some other means and is free to interact with the plasma. Laboratory experiments have shown mobilization of dust under UV and plasma illumination providing insight to the distributions of grain size, speed, and charge once liberated from the surface (Wang et al., 2016). We assume a simple distribution in size, speed, and initial charge and focus on dynamics of grains once liberated. Understanding how grains charge in a plasma and the timescales to do so are important because the motion of grains are dependent on their charge (Borisov and Zakharov, 2014). Dust grains collect charge from various currents including; photoemission, secondary particle emission, and the collection of photoelectrons, solar wind ions, and solar wind electrons. Currents to the grain depend on the size and potential of the dust grain as well as temperature and density of the ambient plasma. An equilibrium charge is reached when the net current goes to zero with a characteristic charging time inversely proportional to grain size (Horányi, 1996).

Previous work has explored plasma conditions conducive for dust transport and indicated that strong dust activity is expected in the terminator regions, agreeing with LEAM and Surveyor observations (Borisov and Zakharov, 2014; Colwell et al., 2005; Farrell et al., 2007; Wang et al., 2009). It has also been shown that ballistic trajectories trap grains in topographic relief and electrostatic forces drive transport to shadowed regions (Colwell et al., 2009; Hughes et al., 2008; Poppe et al., 2012). Furthermore, simulation and experimental efforts have shown that under a wide range of sheath configurations dust grains on the order of 10 nm–10 μm can stably levitate (Pines et al., 2011; Nitter et al., 1998; Colwell et al., 2007; Poppe and Horányi, 2010; Robertson et al., 2003; Sickafoose et al., 2002). Although previous work has explored lunar dust dynamics under varying solar conditions (Poppe and Horányi, 2010), sheath transitions (Nitter et al., 1998), terminator effects (Borisov and Zakharov, 2014; Farrell et al., 2007), and other influences, the role of topography under varied illuminations is not well constrained with regards to effects on dust distributions and dynamics.

2. Plasma and dust models

2.1. Plasma PIC code

The dayside near-surface plasma environment was modeled via a three-dimensional PIC code at discrete SZAs for two topographies. The SZA is defined as the angle between the sun and zenith with negative SZA's towards sunrise (i.e. 0° at noon and −90° at sunrise). A complete description of the PIC code and its capabilities can be found in P1. The topographies chosen were: (1) a simple crater with a diameter of 7 m and depth of 1 m; and (2) the same crater with the addition of a 1 × 1 × 1 m block on the sunrise-side of the crater rim to understand effects due to asymmetry.

In order to obtain a model of the plasma environment encompassing the full dayside lunar conditions, the PIC code was run for SZAs starting at sunrise and increasing by 15° until sunset. Plasma conditions intermediate to the discrete cases were calculated with a linear interpolation in time. For example, the plasma environment when the sun is 7.5° above the horizon is found by equally weighting the conditions at sunrise and when the sun is 15° above the horizon. The solar wind was assumed to have a density of $1 \times 10^7 m^{-3}$, flow speed of 450 km/s, and made up of electrons and ions with a temperature of 10 eV. The photoemission current from the surface was set to $4.5 \times 10^{-6} \mu A\ m^{-2}$ at the sub-solar point, producing 2.2 eV electrons (Feuerbacher et al., 1972). The photoemission current decreased as $\text{Cos}(\alpha)$, where α is the angle between the surface normal and the incident solar radiation and is calculated along the surface to account for surface relief.

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