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Dust environment of an airless object: A phase space study with kinetic models

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ABSTRACT

The study of dust above the lunar surface is important for both science and technology. Dust particles are electrically charged due to impact of the solar radiation and the solar wind plasma and, therefore, they affect the plasma above the lunar surface. Dust is also a health hazard for crewed missions because micron and sub-micron sized dust particles can be toxic and harmful to the human body. Dust also causes malfunctions in mechanical devices and is therefore a risk for spacecraft and instruments on the lunar surface. Properties of dust particles above the lunar surface are not fully known. However, it can be stated that their large surface area to volume ratio due to their irregular shape, broken chemical bonds on the surface of each dust particle, together with the reduced lunar environment cause the dust particles to be chemically very reactive. One critical unknown factor is the electric field and the electric potential near the lunar surface. We have developed a modelling suite, Dusty Plasma Environments: near-surface characterisation and Modelling (DPEM), to study globally and locally dust environments of the Moon and other airless bodies. The DPEM model combines three independent kinetic models: (1) a 3D hybrid model, where ions are modelled as particles and electrons are modelled as a charged neutralising fluid, (2) a 2D electrostatic Particle-in-Cell (PIC) model where both ions and electrons are treated as particles, and (3) a 3D Monte Carlo (MC) model where dust particles are modelled as test particles. The three models are linked to each other unidirectionally; the hybrid model provides upstream plasma parameters to be used as boundary conditions for the PIC model which generates the surface potential for the MC model. We have used the DPEM model to study properties of dust particles injected from the surface of airless objects such as the Moon, the Martian moon Phobos and the asteroid RQ36. We have performed a (v_0, m/q)-phase space study where the property of dust particles at different initial velocity (v_0) and initial mass per charge (m/q) ratio were analysed. The study especially identifies regions in the phase space where the electric field within a non-quasineutral plasma region above the surface of the object, the Debye layer, becomes important compared with the gravitational force. Properties of the dust particles in the phase space region where the electric field plays an important role are studied by a 3D Monte Carlo model. The current DPEM modelling suite does not include models of how dust particles are initially injected from the surface. Therefore, the presented phase space study cannot give absolute 3D dust density distributions around the analysed airless objects. For that, an additional emission model is necessary, which determines how many dust particles are emitted at various places on the analysed (v_0, m/q)-phase space. However, this study identifies phase space regions where the electric field within the Debye layer plays an important role for dust particles. Overall, the initial results indicate that when a realistic dust emission model is available, the unified lunar based DPEM modelling suite is a powerful

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tool to study globally and locally the dust environments of airless bodies such as planetary moons, Mercury, asteroids and non-active comets far from the Sun.

1. Introduction

The Moon is the best known example of the so-called direct plasma–surface interaction where plasma interacts directly with the surface of the object. This direct interaction takes place at the lunar surface because the Moon has neither an atmosphere nor a global intrinsic magnetic field, which could change the motion of charged particles near the surface. Thus, the Moon is an ideal object to study various physical processes near the surface, which are anticipated to occur on the so-called airless bodies, like asteroids, other planetary moons in the Solar System and non-active dusty comets.

One can anticipate that many physical parameters affect surface processes near the lunar surface (see e.g. Kallio et al., 2012, and discussion therein): (1) the density, bulk velocity and temperature of the solar wind protons and electrons; (2) secondary particles (electrons, positively and negatively charged ions) resulting from the impact of the solar wind onto the surface; (3) photoelectrons from the surface in places exposed to the sunlight; (4) charged dust particles above the surface, which are also sinks and sources of charged particles like the surface itself; (5) the interplanetary magnetic field (IMF), the magnetic field associated with the Earth's magnetosheath or with the magnetosphere. Furthermore, possible local magnetic anomalies affect the properties of plasma, for example, reflection of the solar wind electrons and protons from and above the surface requiring e.g. hybrid modelling beyond the Debye scale; (6) the convective electric field associated with the flow of the solar wind, with the electric field in the Earth's magnetosheath or in the magnetosphere (e.g. Kallio and Facskó, 2015). Moreover, there is an electric field within the Debye sheath (or the Debye layer) where the plasma is not quasi-neutral. Furthermore, the solar radiation varies due to temporal variations of the Sun. The intensity of the solar radiation at a given point on the lunar surface varies also with the orbit of the Moon around the Earth. Moreover, physical and chemical properties of the locations on the lunar surface from where the charged particles originate vary (e.g., mafic basalt flows or crustal anorthositic material) vary. Finally, surface processes are affected by topographical variations due to lunar landscapes (e.g. Dyadechkin et al., 2015).

In addition to the aforementioned physical parameters and processes the lunar near-surface is highly important for basic space plasma physics research. Such research is also needed to improve the understanding of the interaction between the dust particles on the lunar surface and the Debye layer that directly affect the technical and scientific instrumentation deployed on the lunar surface during different missions. Ultimately, these effects can pose potential hazard to humans (e.g. Linnarsson et al., 2012). In addition, laboratory experiments have shown that due to the electric field near the surface the dust particles can easily be displaced (Wang et al., 2010) potentially causing malfunctions of moving spacecraft parts and space instruments existing on the lunar surface. Moreover, dust can contaminate astronomical observations in the infra-red, visible and UV wavelength ranges (Murphy and Vondrak, 1993; Stubbs et al., 2006). Lunar dust has also been observed far above the surface (see e.g. references in Stubbs et al., 2006) suggesting that dust may have global effects.

Space weathering caused by micrometeorites, galactic cosmic rays and solar energetic particles erode, and vaporise dust grains and regolith on the lunar surface (see e.g. Jordan et al., 2015). However, the difference between dust on the Earth and on the Moon is that on the Moon there is no Earth-like wind or water erosion of dust particles. Therefore, small lunar dust particles can have very sharp edges and reactive broken chemical bonds (e.g. Liu and Taylor, 2011; Liu et al., 2008; Linnarsson et al., 2012). When entered into the lungs of an astronaut, the small sharp dust particles are therefore a potential health hazard. Generally speaking, lunar dust is more chemically reactive, has large surface areas, and is composed of sharper jagged edges than Earth's dust (Cain, 2010). Properties of dust are therefore a critical issue that has to be taken into account when a crewed lunar mission is planned.

A comprehensive lunar dust model should consider three different space regimes. It should include (1) a global model that gives properties of the solar wind plasma impacting on the surface, (2) a local model of the electric field above the lunar surface which accelerates dust particles, and (3) a global model which gives the density of dust around the Moon. Towards this goal, the present study focuses on three different but connected models. A global hybrid model gives the properties of protons above the surface. A local 2D full kinetic model is then used to derive the surface potential at different Solar Zenith Angles (SZA) near the surface. Finally, a global Monte Carlo model is used to derive three dimensional densities of the dust particles escaping from the surface. The comprehensive lunar dust model is then applied to study the 3D dust density profiles for the Moon, the Martian moon Phobos and the asteroid RQ36 to cover a large size range of planetary objects.

The paper is organised as follows. First the three developed models are described. The capability of the models is demonstrated with a phase space study where the models are used to derive 3D dust densities for the Moon, Phobos and the asteroid RQ36 for parameters entered manually and for two different dust emission models: a homogeneous dust emission for the surface, and a point source at the subsolar point. For parameter evaluation, initial dust particles were chosen from a range that makes it possible to analyse effects of the surface electric potential and, consequently, the capacity of the developed modelling suite to study various airless bodies. Finally, lessons of the analysed cases and a roadmap for future more sophisticated dust models are discussed.

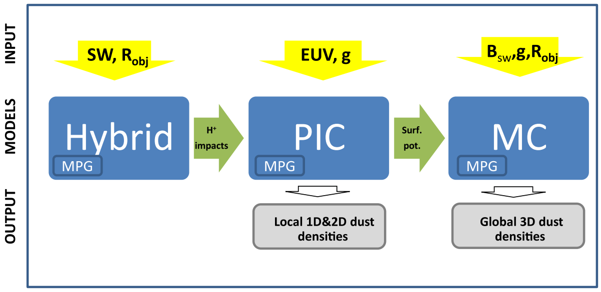

Fig. 1. Overview of the three models in the DPEM modelling suite: [1] a 3D Hybrid model, [2] a 2D electrostatic full kinetic Particle-In-Cell (PIC) model, and [3] a 3D Monte Carlo (MC) model. All three models have also their own 3D Maxwellian Particle Generator, MPG, to inject particles into models. Models are connected to each other by a one-way relationship: The PIC model uses the impacting H^+ ions derived by the hybrid model while the MC model uses the surface potential calculated by the PIC model. Input parameters for the models are the solar wind (SW), the radius of the object (R_{obj}), the gravitational force (g) and the interplanetary magnetic field (B_{sw}). The physical output dust parameters are 1D, 2D and 3D density profiles.