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Thermal analysis of boulders on the 67P/Churyumov-Gerasimenko comet

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Abstract

Through the data acquired by the OSIRIS camera [1], the surface of 67P/Churyumov-Gerasimenko comet (hereafter 67P) appears as a collection of morphological contrasts, with a huge variety of terrains and geological features [2]. The presence of large boulders is one of the ubiquitous, and most important morphological features of 67P: such features can be found both isolated and/or in cluster and their distributions depend on the formation and evolution they have undergone [3]. The analysis of thermal properties of boulders on a comet is pivotal in order to add relevant information to the composition and the structure of the comet itself. Thermal stresses are driven by thermal expansion and contraction of the cometary material too, this a natural tendency of the material in changing its shape, area and volume in response to thermal gradient. Both the expansion and contraction are elastic processes, but they are not enough to induce stresses in the material. Stress can be induced if the expansion or contraction of the material are constrained, or there are different layers of the material bonded each other that are expanding or contracting at a different rate. Furthermore, when a comet approaches the Sun, temperature increases and ices sublimate, making boulders unstable and vulnerable. These stresses can lead to the fragmentation of boulders, as thermally rock breakdown is thought to be an active process in the Solar System [4], contributing to the erosion of a cometary or planetary surfaces.

1. Method and preliminary results

In this study we modeled the thermal stresses occurring on boulders located in the Imhotep region of 67P comet, with the aim to i) analyze the heat transfer in airless rock, ii) investigate solid mechanics properties, and iii) quantify stress values beyond which a material failure occurs. Our first approximation is that we considered spherical boulders resting on the surface of the comet, in which we can find two different geometries: the first consists of a sphere made by water or CO_2 ice mixed by material in form of agglomerated particulates, surrounded by a frost layer. In the second model, the boulder is described as a sphere made by a porous medium whose icy part is sublimated, leaving some residual gases trapped in the porous structure [5].

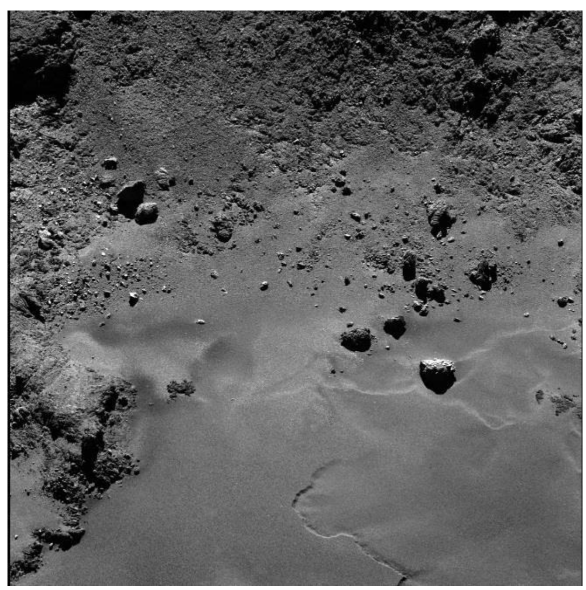

Figure 1*: OSIRIS NAC image taken on 29 September 2014. The scale of the image is 0.35 m/px. This area is located in the Imhotep region [2].*

Regarding the choice of materials, we decided to consider water and dry ice, dunite and graphite as solid part. As proposed by Cheng, S. C. et al. (1969) [6], we calculated the thermal conductivity and thermal inertia for each case. Figure 2 shows an example of the calculated thermal conductivity for a boulder made by dunite as a continuous material and water ice as discontinuous material. We performed our calculations with a temperature ranging between 150 and 230 K. Then, we calculated the relative thermal inertia values on all cases. After calculating the values of thermal conductivity and thermal inertia, we used these values as properties to be assigned to the two geometries in order to simulate the heat propagation, the temperature variation, and the behavior of thermal stress inside the different boulders. We performed this analysis using COMSOL Multiphysics, a 3D Finite Element simulator, calculating the position of the Sun with respect to the selected region of the 67P using the NAIF SPICE Toolkit. After testing the model, we performed the same analysis for boulders with different shapes, varying the values of compactness, circularity, convexity, and complexity, in order to correlate the stress trend with the shape variation.

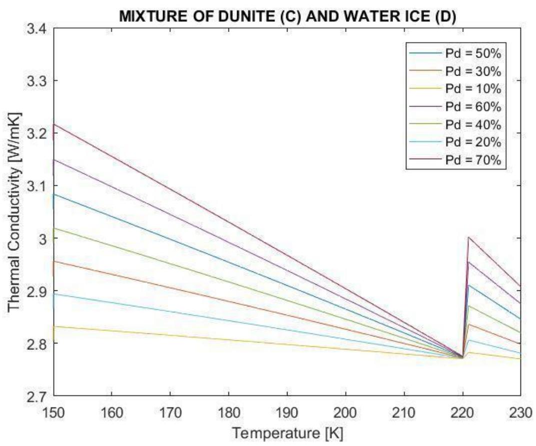

Figure 2: *Thermal conductivity of a boulder made by dunite as a continuous phase, and water ice as discontinuous phase. Each percentage Pd represents the amount of discontinuous material dispersed in the continuous one.*

Our preliminary results show that the establishment of a daily thermal gradient leads to very high thermal stress concentrations, having in some situations temperature variations of the order of hundred Kelvin. Moreover, the analysis performed for boulders with different shapes shows how corners and edges are sensitive parts to thermal fatigue.

Acknowledgements

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Outgassing of H_2O/CO_2 mixtures

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Abstract

Gas diffusion plays an important role in understanding comet activity as the diffusion process directly effects the energy balance within a cometary surface and, therefore, influences processes like surface evolution and dust production. Here, we introduce a novel selection of experiments examining the gas production mechanisms of cometary like porous aggregate layers consistent of H_2O, CO_2 and SiO_2. With our results we provide a set of equations relevant for comet surface evolution and dust activity simulations.

1 Introduction

Models of gas transportation through porous media are used to calculate the production of volatiles of active comets, to resolve the flows of energy in the cometary surface and finally to model dust activity and evolution of the surface layers. Most scientific works consider either the results of numeric gas transport simulations [5] or laboratory measurements with a two layer setups comprised of solid volatile ices with an overlain, relatively compact, dust layer [4].

However, there is strong evidence that the building blocks of comets consists of porous aggregates of mainly H_2O, CO , CO_2, SiO_2, organic components and other volatiles [2, 1, 3]. Hence, describing the processes of gas diffusion through porous layers of pebble like material presents the next step in understanding the processes behind cometary activity and dust production.

To assess the diffusion mechanisms of cometary surfaces, we examine the gas flow of H_2O and CO_2 ices through a porous pebble layer in dependence of the samples temperature, layer height and composition of the pebbles.

2 The experiment setup

Two types of samples are examined within this work. First we analyze a system in which porous pebbles of volatile and inactive components are mixed together. Each aggregate consists of only one constituent. We refer to this system as the separately mixed sample. Inactive components are either SiO_2 or H_2O, depending on temperature. Secondly, we analyze a system in which the volatile and inactive components are intrinsically mixed in each aggregate. We refer to this system as the intrinsically mixed sample. A draft of both systems is shown in figure 1. For both types of samples, we analyze the deviation of the samples gas production rate from that of a solid, barren ice in dependency on the samples temperature as well as on the thickness of the porous layer.

Each experiment consists of the following steps: after production, the sample is handled at liquid nitrogen temperature to ensure the unaltered status and is subsequently transfered into the nitrogen cooled measurement chamber. Directly following, the experiment chamber is evacuated. As soon as a steady background pressure is reached, the sample is heated to a constant temperature and the outgassing rate measured as the volatile boundary retreats into the sample.

To measure the gas production rate, we utilize the fact, that at low sample temperatures, as found on comets, the outgassing rate of H_20 and CO_2 ices is such low that the production rate is proportional to the density of the gas flow emerging from the sample. Therefore the gas production rate is proportional to the pressure above the sample and can be calculated from the latter. In our setup, the pressure above the sample is recorded by a hot cathode pressure sensor or a mass spectrometer (to differentiate the partial pressure of the gas species). A chopper system is used to separate the background pressure from the sample pressure.

Since the pressure produced by the sample must be significantly higher than the background pressure to be measured, the experimental setup comprises a

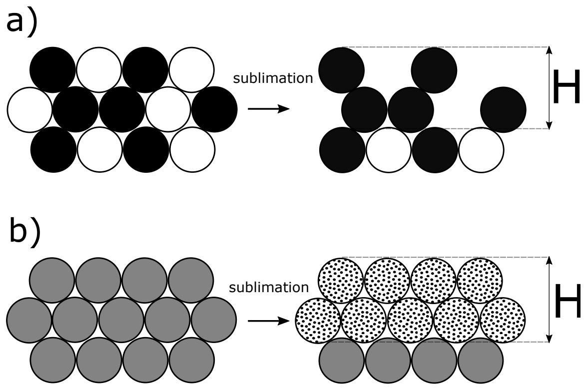

Figure 1: Schematic visualization of the different type of mixtures and the effect of material loss: Separately mixed model with black inactive pebbles and white active pebbles a) and the intrinsically mixed model with gray pebbles consisting of active as well as inactive components while dotted pebbles symbolize pebbles depleted of active constituents b). H is the height of the inactive layer.

two stage rotary vane pump and a turbo molecular pump. A comprehensive explanation of the measurement principle can be found in [4].

3 The diffusion model

At the beginning of each experiment, the outgassing rate equals that of a solid ice sample. However, with beginning loss of material, the boundary of the active volatile component retreats into the sample. The remaining, overlaying layer of inactive material dampens the gas flow. The ratio between the dampened gas flow and the gas flow of a solid sample is described by the so called diffusion coefficient and depends on the thickness of the overlaying layer. The thickness of the layer can be derived by comparing the sublimated mass calculated from the measured production rate. Examples of analytical models and simulations can be found in [5].

4 Results and conclusions

Our experimental setup enables us to measure the production rate of a porous pebble mixture composed of H_20 and CO_2 ices and SiO_2 dust in dependency of the thickness of the inactive layer and the ices temperature. Based on the measured data we develop a diffusion model that depends on the mixing type (intrinsic or separate) of the aggregates, the temperature and the thickness of the inactive layer. These models can be used by comet simulation models to improve the understanding of cometary activity such as subsurface evolution and dust release. The data and model will be presented at the EPSC 2018 in Berlin.

Acknowledgements

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Modelling a wheel in the regolith of a small body – a Project Chrono study

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Abstract

The objective of this study is to examine Project Chrono as a modelling tool for wheel-regolith interaction in the milligravity regime of a small body. The composition and behavior of regolith on small bodies is unknown and may vary widely from one body to the next. Nevertheless, it is generally accepted that cohesion plays an important role and how this material settles and flows. In this poster, we present how Project Chrono, an open source physical engine allowing for fast parallelized simulation, can be adapted and utilized to model the plowing of a wheel, or any other object, in regolith with cohesive properties. This cohesive model and its implementation are discussed as well as other parameters and options of Project Chrono.

1. Introduction

Many missions have made it their goal to explore the multitude of smaller bodies in the solar system and, if possible, in situ. Landers have been envisioned in many proposals (e.g. Discovery 2014 proposal BASiX) and realized with Philae aboard Rosetta. Mobile explorers, like hoppers and rovers, offer the possibility to explore multipe sites. The hopper solution, using an external or internal mechanical momentum device to jump from places to places, has been examined for locomotion on a small body (e.g. Mascot aboard Hayabusa 2).

Because of the low gravity, a rover can have difficulty finding traction. On the other hand, the preponderance of cohesion in the regolith behavior [6] could provide the traction that weight would in higher gravity contexts. Moreover, a rover could allow for easier operations and mobility.

To decide on the means of transportation of such a lander, it is thus essential to understand how a wheeled vehicle would interact with the regolith in a low-gravity environment. Discrete element method (DEM) simulations are a staple instrument for soil-object interactions on earth and come in two varieties, hard-sphere DEMs and soft-sphere DEMs. For a bed of regolith, we have chosen to use soft-spheres.

To carry out these simulations, we have chosen Project Chrono. Project Chrono is an open-source physics engine that allows a wild range of simulations, notably DEMs [4]. However, the specific properties of regolith requires a careful examination of the forces modeled in Project Chrono, and in particular cohesion.

2. Project Chrono

To build an accurate model, it is required to grasp the intricacies of how Project Chrono models the grain-grain and grain-vehicle interactions.

Project Chrono employs a SSDEM adaptation by the name of smooth contact method (SMC) alongside a HSDEM adaptation named non-smooth contact method (NSC). The SMC model allows the user to specify a set of material parameters that influence how an object interacts with others. These are Young's modulus E, Poisson's ratio ν, the coefficients for static and sliding friction μ_s and μ_k as well as the coefficient of restitution (COR) e. Adhesion can be set as a constant force or according to the Derjaguin-Muller-Toporov (DMT) model [5]. All these parameters are then used to calculate the stiffness and damping coefficients, which are necessary to model collisions. Project Chrono features implementations of a Hookean and a Hertzian contact force model to simulate the repulsive forces experienced by colliding objects [1]. They do however exhibit some behaviour one would not intuitively expect.

For instance, as displayed in Figure 1 and 2, testing the coefficient of restitution delivers the expected results for high CORs, but shows a significant difference for near-zero CORs. This is a property inherent to many Hertz/Hooke-based force models [2], but might require modification as very low CORs may occur for fluffy regolith particles. Implementing a dif-

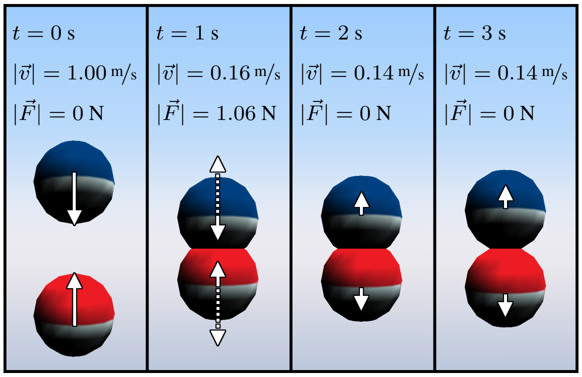

Figure 1: Two spheres with a set coefficient of restitution $e = 0$ and Young's Modulus $E = 2$ Pa colliding. Their velocity is shown as straight arrows, the contact force as dashed arrows. They do not experience the force for the whole duration of overlap and retain an outgoing velocity.

ferent contact force model such as the one described in [3], which exhibits a closer agreement between pre- and post-restitution coefficients is possible in Project Chrono and should be considered an option if so desired. Similar investigation will be done for the implementations of static and kinetic friction as well as cohesive forces. Rolling friction seems to be available only for the HSDEM NSC model and will need some attention to use it in the SSDEM simulation.

The poster will expand on Project Chrono implementations of the different material properties (including COR, friction coefficients, cohesion, etc.).

3. Application to a wheel

To simulate the conditions on a regolith bed on a small solar system body, a large number of individual soft spheres will be subject to gravity on the scale of $10^{-4} - 10^{-2}$ m/s². The material properties of regolith are not well understood and the simulation should be run for different sets of estimations (particle distribution, physical properties, etc.). Then a single wheel is placed on top and we observe its traction and plowing performance.

The poster will show how Project Chrono can be used to carry out these simulations with the presentation of some preliminary results. Although this setup can be used to simulate a wheel in regolith, it could also be used to model any mechanical device penetrating regolith, such as mechanical sampler. Upon completion the code will be made available as open-source.

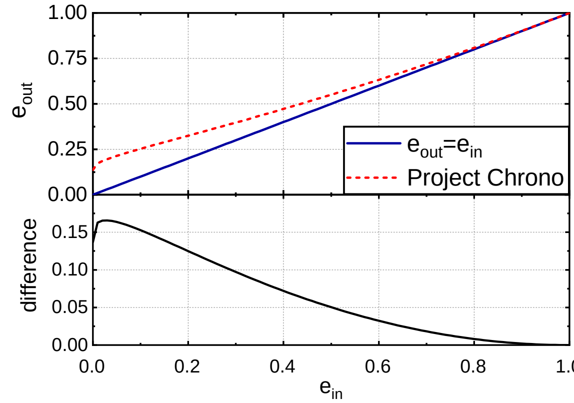

Figure 2: Comparison of the measured coefficient of restitution e_{out} and the pre-set e_{in}. The straight blue line represents a perfect model where both are the same, the dashed red line Project Chronos implementation. Their difference is shown in the black line, which outlines a good match for high coefficients of restitution, but a higher divergence for smaller ones.

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The Lagrangian SPH approach applied to the cometary gas-dust emission.

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Abstract

The evolution of the dust and its interaction with gas systems constitute an important physical feature characterizing the minor bodies of the Solar System. In this work, we aim to discuss some suitable numerical Smoothed Particle Hydrodynamics (SPH) techniques to model the interaction and time-evolution of gas and dust systems. We focus our attention on the peculiar problem of jets expelled by the cometary surfaces, in the framework of the recent ESA Rosetta fly-by mission which provided a deep analysis of the properties of the comet 67P/Churyumov-Gerasimenko, during its approach to the internal Solar System.

1 Introduction

Among the minor bodies, comets constitute the most important trace of the origin of the Solar System, since their nucleus contains matter built in the first phases of the protoplanetary disk condensation and remained nowadays unpreserved. Nevertheless, cometary nuclei, especially the ones belonging to short period comets, can undergo important changes during their approach to the Sun. Cometary activity constitutes a series of important processes involving the expulsion of sublimating gas which drags out dust grains. It is a very important mechanism which can give us important information about the internal structure of the nucleus and, at the same time, can explain the matter observed in the coma. We have a few examples of direct observations of gas emission. Fig.1(a), shows a trace of matter expulsion from 1P/Halley through the radiation emitted by H_2O photo-dissociation and dust grains ([1]). As we can see from the picture, collimated structures (jets) of water gas are emitted from the surface.

Generally, a direct observation of the surface activity is not possible, since the very large coma and the dust tails are together the primary and, often, the only source of radiation we can detect. They obstruct a detailed observation of the expulsion of matter out of the cometary surface. For such reason, we need a realistic model to connect the rate of gas and dust expelled to the one observed.

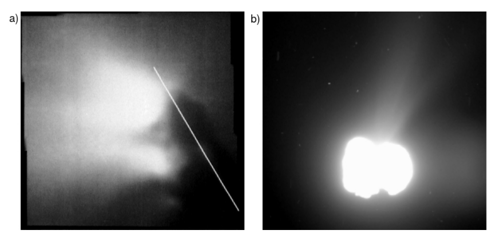

Figure 1: Panel (a): nucleus activity of 1P/Halley comet, observed with the ESA's Giotto spacecraft. Panel (b): nucleus activity of comet 67P/C.G., from OSIRIS camera of probe Rosetta.

2 Modellization of Cometary Activity

2.1 Basic model

A simple model for a cometary jet consists in assuming a comet to be spherical and considering a circular hot active region from which the ice, trapped in the porous rock, sublimates and flows away by dragging a little number of dust grains (typical size ranges from 10^{-7} to 10^{-3} m). The main interaction between dust and gas is given by the drag force i.e. the net momentum impressed by the gas to the surface of the dust grains. According to a simple model in which the grains are spherical, it has been found the following expression for the acceleration impressed to a single dust particle:

$$\vec{a}_d = \frac{\vec{F}_d}{m_d} = \frac{3}{8}\frac{C_D \rho_g |\Delta\vec{v}|}{a\rho_d}\Delta\vec{v}\,. \qquad (1)$$

It depends mainly on the ratio $\frac{\rho_g}{\rho_d}$ between the local gas density and the bulk grain density, on the grain size a, and on the relative velocity of the two components $\Delta\vec{v}$. C_D represents the so called *drag coefficient* (see [6]).

A systematic ejection activity could deplete the surface while forming a crater. The following sublimation of gas from the base of the craters can drive the gas to a preferential direction and, as a result, the jet turns out to be collimated.

2.2 SPH numerical simulations for gas and dust

SPH constitutes a suitable and well-known approach to integrate the fundamental hydrodynamical equations that describe the time evolution of a fluid. The SPH is able to schematize a system by means of a distribution of free points (pseudo-particles) which give a discrete and macroscopic representation of the fluid. The fundamental quantities, like density or pressure gradient, are then evaluated through suitable interpolations over a finite discrete domain. For an exhaustive explanation see, for example, [5].

In a simple framework in which the dust is made of equal-sized grains, it can be coupled to the gas and treated as a second component by using the same basic SPH formalism (see [4]). The dust component is thus represented, like the gas, by a set of interpolating particles. Moreover, if the dust grains constitutes a full non-collisional system, its pressure can be set to zero and thus no equation of state needs to be used. The evolution of the new component is thus described by only its equation of motion, in which the acceleration field is given by a drag term strictly connected with the drag acceleration (equation [1]), and an additional term which depends on the macroscopic local *volume-density* of the dust.

Differently from a Eulerian approach with fixed grids, the Lagrangian SPH methods allow easily to reproduce the shape and density distribution of a system: the higher the density, the more the concentration of points, without introducing any artificial grid. Moreover, during the time evolution, the particles follow the actual motion of the fluid and participates to the local and global density variation. Boundary conditions, like walls, or the flux of gas from a surface with a prefixed velocity, can be included with suitable techniques which adopt static particles (see [3, 2]). All these features turn out to be well appropriate to investigate the surface activity of a comet, in particular for 67P/CG, which is characterized by an irregular surface and for which the geometry of dusty-gas jets can be very complex if compared with the simple spherical models usually adopted for the cometary shape. Fig.1(b) illustrates a shot of the comet during its approach to the internal Solar System (at a distance of 550 km from the Sun) which shows indeed a very irregular shape.

3. Aims and Conclusions

Some examples of applications of the SPH algorithms on gas plus dust multi-fluid are presented. In particular, we aim at focusing our attention on collimated jet emissions from a crater, in which the dynamical evolution of matter is strictly dependent on the environment conditions (shape of the crater, surface temperature) and on the physical properties of dust grains (bulk density and size).

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Europa's Ice-Related Atmosphere: The Sputter Contribution

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Abstract

Europa, the innermost and smallest of the four Galilean moons orbiting Jupiter, is constantly bombarded by Jupiter's magnetospheric plasma. This plasma interaction, together with sublimation during the day, lead to the formation of a tenuous atmosphere, also called exosphere. In this work we present the sublimation and sputter contribution to Europa's exosphere, computed by Monte-Carlo modeling. In addition, we will compare the resulting density curve to the measurement capabilities of PEP / NIM on JUICE.

1. Introduction

Europa, Jupiter's innermost icy satellite, is embedded well within Jupiter's magnetospheric plasma, an intense flux of ions and electrons that approximately co-rotate with Jupiter. With Jupiter's rotation period being substantially shorter than Europa's orbital period, the Jovian plasma constantly flows over Europa from its trailing hemisphere and sweeps ahead of it on its orbital motion. The plasma itself can be thought of as consisting of two populations: the cold, thermal plasma with energies ranging from eV to keV and the hot, energetic plasma with energies ranging from keV to MeV. As the plasma encounters Europa's icy surface, two processes are dominating with respect to the atmosphere: radiolysis, altering the ice physically and chemically, and sputtering, which releases surface material from the ice matrix to form a tenuous atmosphere.

2. JUICE Mission

In early May 2012 ESA announced the selection of JUICE as the first large-class mission of the ESA Cosmic Vision Program 2015-2015 [1]. The launch is planned for June 2022, which would put JUICE in the Jovian system by 2030. In February 2013, 11 scientific instruments have been selected to fly on JUICE. One of these 11 instruments is PEP, the Particle Environment Package [2]. PEP will deliver a 3D view of the Jovian Plasma system by measuring ions, electrons, energetic neutral atoms (ENAs) and neutral gas simultaneously over nine decades of energy from <0.001 eV to >1 MeV with full angular coverage. To achieve this full particle, energy and angular coverage, PEP incorporates six different types of sensors, one of which is NIM, the Neutral and Ion Mass spectromenter.

3. NIM Instrumentation

NIM is a highly sensitive neutral gas and ion mass spectrometer designed to measure the exospheric neutral gas and thermal plasma at Jupiter's moons with a very high mass resolution and unprecedented sensitivity. The detection level for neutral gas is 10^{-16} mbar for a 5-second accumulation time [3], which corresponds to a particle density of ~1 cm^{-3} . The mass resolution is $M/\Delta M > 1100$ in the mass range 1–1000 amu, and NIM's energy range is ≤ 5 eV for neutrals and <10 eV for ions. NIM's science goal is to analyze the extended atmospheres of Europa, Ganymede and Callisto, in particular the neutral and the ionized component.

4. Monte-Carlo Modeling Results

In this work we calculate the sputter contribution of Europa's icy surface to its exosphere, and show that both the cold, co-rotating thermal plasma as well as the hot, omnidirectional energetic plasma are of comparable importance for the formation of Europa's exosphere. Our modeling results are based completely on first principles, that is no scaling of surface fluxes to observed densities are applied. Instead, we apply current best knowledge of Jupiter's plasma properties, as well as most recent laboratory results on ice sputter yields to our Monte Carlo model, to calculate Europa's exosphere ab initio. In particular, this work is the first to incorporate laboratory measurements of electron ice sputter yields in an Europa atmosphere calculation. Similarly to previous modeling results, our calculations show that Europa's exosphere is dominated by a bound, thermalized O_2 atmosphere close to the surface (below ~1000 km), and by an extended corona of light H_2 molecules at higher altitudes.

5. Summary and Conclusions

According to NIM specifications, NIM will be able to measure all water-related species in Europa's exosphere. Both the thermalized O_2 atmosphere close to the surface and the extended corona of light H_2 molecules at higher altitudes will be clearly visible in the NIM mass spectra.

Our models will help to distinguish between different exospheric components (e.g. sublimated versus sputtered contributions), and explain variability in Europa's exosphere due to changing conditions.

NIM, with its high mass resolution, range and sensitivity, will be able to help contribute to the habitability assessment of Europa by being able to investigate localized patchy regions of the exosphere indicative of sub-surface venting and to resolve chemical composition. Most important, NIM will help to investigate the potential for the emergence of life in the galactic neighborhood and beyond.

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Core dynamo in mantle-stripped asteroids

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Abstract

Core dynamo is one of the most efficient mechanism to produce magnetic field in the planetary bodies of the solar system. However, also minor bodies like asteroid show evidence of a past magnetic field: Vesta [1, 2] and Psyche [3, 4] are the most common examples. In particular, Psyche is the metallic residual core after a mantle-stripping. In this regard, it is interesting to evaluate how the thickness and composition of the residual overlying rocky lid influences the thermal convective evolution of the core [5].

1. Introduction

The generation of a magnetic field is possible if the core of the body is: 1) metallic; 2) liquid; 3) in convection. In the small bodies of the solar system, these three conditions are hardly respected due to the low temperatures generally reached in their interior. Typical timescales of core dynamos are of the order of 10-100 Myr after the formation of the body [6, 7]. The role of the "crust" (the upper silicate layer) is crucial in the core dynamo evolution. In this work we have analyzed different initial configurations, characterized by different crustal thickness. The methodology adopted in this work is to investigate the thermal convection evolution of these bodies and to use a scaling law (based on the mixing length theory) in order to estimate the magnetic field evolution.

2. Numerical Model

The model solves the Navier-Stokes equations with the buoyancy term, in the Boussinesq approximation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \vec{\nabla} \cdot [(\eta \vec{u} \times \vec{u})] = -\vec{\nabla} \cdot p\vec{I} + F, \quad (1)$$

where η is the dynamic viscosity (considered temperature-dependent), $\vec{u}$ the convective velocity, ρ the density, p the pressure and F is the bouyancy term.

We also impose that:

$$\rho \left(\vec{\nabla} \cdot \vec{u} \right) = 0, \quad (2)$$

which physically means no sinks or sources.

The system of equations is completed by the heat equation:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \vec{u} \cdot \vec{\nabla} T + K \vec{\nabla} \cdot \vec{\nabla} T = 0, \quad (3)$$

where c_p is the specific heat and K is the thermal conductivity.

The convective velocity is calculated according to [9]:

$$u = \left(\frac{4\pi G \alpha R_c^2 F_{conv}}{3c_p} \right)^{1/3}, \quad (4)$$

where α is the thermal expansivity, R_c the core radius, F_{conv} is the convective, estimated through the heat equation.

A non-dimensionalisation approach is adopted, following the scheme of [8], in order to control the thermal evolution through two key-parameters, the Prandtl and Rayleigh numbers. The core (100 km in size) is modeled as a mixture of iron and nickel, while the crust has the typical thermal properties of the silicate rocks. The initial temperature is such that the core is initially fully melt.

3. Results $\&$ Conclusions

The shielding of the crust is crucial in the duration of the melting of the core and of the dynamo. In case of very thin crust (1 km) the dynamo is not generated, while in the other cases we have explored (10 to 40 km crustal thickness), the timespan of the dynamo core ranges from 25 to about 70 Myr, less than the typical values found in literature [6,7]. A comparison with the cooling rates of the IVA meteorites is also provided. This study could support, from a theoretical point of view, future missions dedicated to this kind of asteroids, like Psyche.

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ESA Micro-meteoroid models applied to exosphere formation of the Jovian icy moons

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Abstract

Simulations of the dust environment around the Jovian icy moons are used to model the formation of exospheres by means of meteoritic impact vaporization occurring on their surfaces.

1. Introduction

GALILEO probe and the Hubble Space Telescope found evidence for tenuous exospheres around the Jovian moons Ganymede, Callisto and Europa. The composition of those thin atmospheres gravitationally bounded around the moons is largely unknown and their characterization would help to understand the mass and energy exchange between the Moons and the Jovian magnetosphere.

Moons' surfaces are exposed to various physical processes that contribute to the formation of their exospheres, like radiolysis, thermal desorption, plasma sputtering and micro-meteorite impacts. In the present work, we focus on the exosphere's formation by means of the the Jovian moons' impact by dust particles, coming both from the Interplanetary environment and impact-generated dust ejecta coming from the satellites.

2. Dust environment models

Models covering two distinct dust particle populations pervading the Jovian system are presented.

2.1. The Interplanetary Meteoroid Environment Model (IMEM)

Primary interplanetary dust impacts are simulated using the prediction of the Interplanetary Micrometeoroid Environment Model (IMEM) computed at Jupiter's Hill radius, taking into account gravitational focusing by the planet.

IMEM is a dynamical evolutionary model built by [1] for ESA. This model starts from the orbital elements of known sources of interplanetary dust: comets and asteroids. The model assumes rotational symmetry around ecliptic pole. IMEM states an applicable distance range from 0.1 to 5.0 AU - from Mercury to Jupiter and beyond - and an applicable mass range from 10^{-18} to 1g. IMEM has no restriction with respect to ecliptic latitudes.

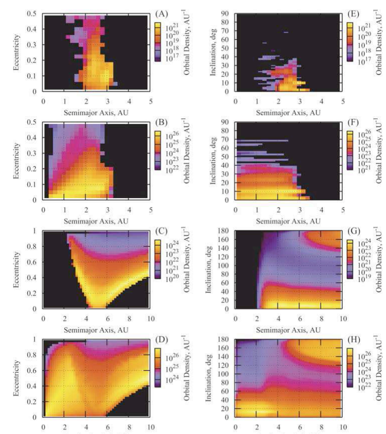

Figure 1: Orbital distributions of interplanetary dust particles in the ESA meteoroid model [1]

Using the IMEM model, the flux of interplanetary impactors for all mass ranges above 10^{-12} kg, expected at the Hill's radius of Jupiter, is computed. Inside the Hill's radius, we apply a formulation of gravitation focusing as described in [2] in order to estimate the increase in volume number density and speed (resulting in an increase of the flux) of the interplanetary grains as function of the radial distance to Jupiter. We convert the mass distribution, grain speed and particle flux to infer the kinetic energy flux entering the Jovian system from the interplanetary space. This kinetic energy flux is distributed isotropically on the moons surface, once corrected for the gravitational focusing, and is the primary energy source for producing secondary ejectas.

2.2. The Jovian Micrometeoroid Environment Model (JMEM)

Impacts of dust particles coming from the Galilean moons (impact generated dust ejectas) and evolving dynamically in the Jovian system are simulated using the Jovian Micrometeoroid Environment Model (JMEM). JMEM has been built for ESA by [3] to provide an estimate of the micro-meteoroid fluences (integrated flux) of dust impacting the ESA JUICE spacecraft [4] along its trajectory in the Jovian system.

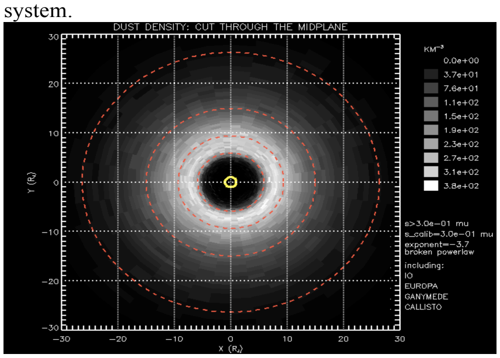

Figure 2: Distribution of the particles for all grain sizes larger than 0.3 micron, as obtained with JMEM model.

The primary source of dust in the Jovian system is the sputtering of the major icy moons by hypervelocity impacts of dust coming from the interplanetary space. The ejected particles that have sufficient velocity to escape the moon's gravity are injected into the Jovian system and their trajectories evolve under the action of various forces: Lorentz forces, radiation pressure including Poyting Robertson drag, solar and moons gravity, plasma drag, and gravitational effects due to Jupiter non-sphericity. The particles dynamical evolution is computed and their distribution of orbital elements is stored, providing a volume number density and velocity of particles across the Jovian System that can be used to compute a flux of impactors on any body which trajectory is given.

3. Exosphere formation

The interactions of both interplanetary dust particles and moon's secondary ejectas with the moons' surface lead to a transfer of their kinetic energy into various phenomena, like fracturing, melting and evaporating refractory and volatile material that assist the exosphere formation. Considering water ice as the main component of the icy moons surface, we compute the total vapor released and analyze the contribution of the different dust populations. According to [5], a single meteoroid impact is assumed to generate a vapor cloud with a mass given by:

$$M_v \approx M_i \left(2 \left[\frac{4 \left(\frac{Q_v}{\vartheta} \right)^{0.5}}{V_i} \right]^{\vartheta - 2} - 1 \right)$$

where is M_v the mass of the impact-induced vapor cloud, M_i is the mass of the impactor, V_i is the impactor's velocity, Q_v is the evaporation heat of the target, and ϑ is a modelling factor.

The total vapor mass is computed by considering the mass and velocity distributions coming from the dust populations described in Section 2. The result will be a total collision-induced production rate distribution as a function of impactor masses and velocities [6], which permits to assess the contribution of the different dust populations to the exosphere formation.

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Transient exospheres and atmospheres in dwarf planets: SPH treatment with composite gas-dust plumes

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1. Introduction

The presence of a stable atmosphere is a characteristic in most of the planets of our Solar System. First, obviously, the four Giant Planets, including the Saturn main satellite Titan. But also the terrestrial planets, with the exception of Mercury, too close to the Sun, present an atmospheric envelope. At the same time, we have different classes of objects, Dwarf Planets, some of the largest asteroids, and the main satellites of the Giant Planets, that can produce thin transient atmospheres or exospheres [1], depending on the production rate of volatiles and on the ratio of the molecular mean free path to the dimension of the envelope. The process can be triggered by impacts with asteroids or large meteorites, or by tectonic activity [3], and also by solar wind events [4]. The lifetime of the envelope itself grows with the ratio of the escape velocity over the mean thermal velocity, and with the extension of the Hill Lobe, i.e. the region where the gravity of the body prevails on that of the Sun or that of the central planet. So, massive, outer and cold bodies are favoured. Another constraint is the stability of the volatiles, and this is verified if the saturation pressure is less then the vapor pressure. For this reason a privileged status is that of the Main Belt, where Ceres [5], Vesta and Pallas should permit the existence of water vapor with reasonable values of production rate. The same is for Pluto [6], where water can exist only as ice, but N_2 CH_4 and NH_3 can have phase transitions. Jupiter and Saturn satellites, on the contrary, and with the exception of Titan, Enceladus and perhaps Europa are penalized, being cold and close to their central planet, by their relatively small Hill radii and by the stability of icy water.

2. Numerical Model

Due to the large range of variation of the main physical parameters of a dusty plume, we have utilized the SPH approach [2] for the study of the hydrodynamical evolution of the plume, and have used some of the basic SPH paradygms in order to study the dynamics of the dusty particles. Vapor escape, when local thermodynamical equilibrium is not possible, due to low density values, has been studied by implementing a Montecarlo algorithm, that calculates the rate of escape of single molecules that experience a reasonable number of collisions ($<$50) before crossing the Hill limit. For the dust, a pseudo-smoothing scale length, similar to the analogous of the SPH model, was introduced in order to have values of the group velocity and viscous drag. The mutual viscous forces between gas and dust have been normalized, to satisfy global momentum conservation. Recondensation of water vapor and sublimation of ice have been also included. The thermal structure of the gas envelope was considered by adding to the transport equation of the thermal energy, an approximate treatment of the radiative diffusion equation. Besides, the balance between sublimation and recombination, and the deposition of dust and icy particles on cold regions of Ceres surface have been also taken into account. Last, the model evaluates the emission from the subsurface, possibly discovered and described in some detail by the Herschel mission in 2014 [5]. This process is simulated by injecting a time dependent flux of SPH pseudoparticles and dust particles [8, 7].

3. Conclusions

In the talk are examined the main parameters of these processes, as loss timescale of a plume, its dependence on the main physical constraint, and the structure of a nearly stationary plume generated by an hot spot on the surface of Ceres.

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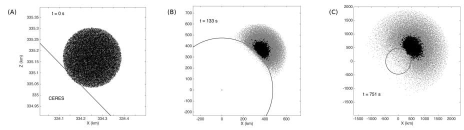

Figure 1: Initial time evolution of a plume generated near the Ceres surface. Here, grey dots represent H_2O vapor SPH pseudoparticles, while the black dots show the dust distribution. Panel (A) corresponds to the initial time, while panels (B) and (C) show different evolutive steps. In panel (C), the velocity of expansion is largely supersonic. The total mass of the plume is 10^{10} kg, the mass fraction of the dust is 10^{-1}. The ensemble is composed by $3 \times 10^4 + 3 \times 10^4$ particles.

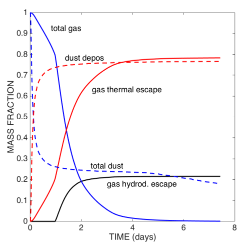

Figure 2: Time evolution of the total mass of the plume inside the Hill Lobe both for H_2O vapor and dust. In the Figure are also indicated the fractions of gas lost both as single non LTE molecules and as LTE gas crossing the Hill boundary. Besides, is also plotted the fraction of dust deposited on the surface of Ceres, at the first time due to the sudden expansion of the plume, and then by gravitational ballistic or orbital infall.

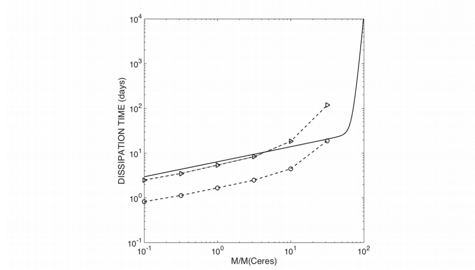

Figure 3: Dissipation timescales of a plume expanding on Ceres or pseudoCeres dwarf planets. These bodies are at the Ceres distance and temperature mean conditions, but with different masses, from 0.1 to 100 times its value. The solid line refers to a nearly-Jeans thermal escape timescale, $t_J = Me/4\pi R_H^2 \rho(R_H) c_s$, where M_e is the mass of the plume, $\rho(R_H)$ is the density at the Hill boundary with radius R_H, and c_s is the sound velocity ar $r = R_H$. The dashed curve with circles represents the effective depletion time up to a fraction 1/e of the initial value, and the upper curve with triangles refers to a depletion factor of 10^{-2}. The mass of the plume is 10^{10} kg.

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Modeling the Evolution of the Acapulcoite-Lodranite parent body: An Insight into a Partially Differentiated Asteroid

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Abstract

We investigate the thermal and structural evolution of the parent body of the acapulcoites and lodranites. We compare the calculations with the differentiation degree and the thermo-chronological data. We obtain a consistent set of parameters that fits the available thermo-chronological data and provide estimates of parent body's size, formation time, orbit of formation, nature of the precursor material and internal structure.

1. Introduction

The acapulcoites and lodranites (AL) are rare groups of primitive achondritic meteorites. Although they have the texture of achondrites, they are compositionally related to ordinary chondrites. Several characteristics, such as oxygen isotope composition and cosmic ray exposure ages indicate origin on a common parent body[1-3]. By contrast with undifferentiated and differentiated meteorites, ALs are especially interesting because they experienced partial melting and only minor melt segregation[4-7]. Thus, unravelling their origin provides important insights into the initial differentiation stage of planetary objects. The information preserved in their structure and composition can be recovered by modeling the thermo-chemical evolution of their parent bodies and comparing it with the laboratory measurements, e.g., closure ages and temperatures. In this study we investigate the thermal and structural evolution of the parent body of the AL meteorites using two models that consider compaction, partial melting as well as metal-rock differentiation, and provide best-fit estimates for the parameters that define the key properties of the parent body. We compare the calculations with the metamorphic temperatures, the differentiation degree and the thermo-chronological data (Table 1). We obtain a set of parameters that fits the thermo-chronological data for the AL-clan (Table 2). Our models provide estimates of the size, formation time, orbit of formation, nature of the precursor material and internal structure of the AL parent body. Based on the differentiation degree we draw conclusions about the compositional and metamorphic variations of the AL meteorites. We establish connections with other achondritic, primitive achondritic, and chondritic meteorites, and place ALs into a general context. We discuss the possibility of a magnetic field and indicate concrete asteroids as potential parent bodies.

Method	Closure T $T^{(c)}$ K	σ_T K	Closure time $t^{(c)}$ Ma	σ_t Ma
	Acapulcoites			
Hf-W	1248	50	4.8	0.7
U-Pb-Pb	720	50	12.6	0.7
I-Xe (fsp)	750	100	9.8	1.6
I-Xe (pho)	700	50	14.8	0.4
Ar-Ar	550	20	21.3	6.0
Pu fission	390	25	131.0	14.0
U-Th-He	393	50	56.3	45.0
	Lodranites			
Hf-W	1298	50	5.7	0.6
I-Xe (fsp)	750	100	16.6	2.3
Ar-Ar	550	20	41.3	10.0
	Chondrule bearing acapulcoites			
Hf-W	1248	50	3.1	0.7
Ar-Ar	550	20	14.3	11.0

Table 1: Closure time and temperature data used for fitting the meteorites (averaged over single groups).

2. Model

On the one hand, a thermal evolution model should fit the thermo-chronological data available. On the other, acapulcoites and lodranites experienced partial but not complete melting and even some small scale melt migration. Therefore, also melting of the metal and silicate rock and differentiation due to the migration of the melts should be considered. We calculated the thermal evolution of the parent body considering heating by short- and long-lived nuclides, temperature- and porosity-dependent parameters, and compaction of porous material. Calculations have been performed using two models. The first model *A* is described in detail in [8], the second model *B* is based on [9,10]. Both solve a 1D heat conduction equation in spherical symmetry considering heating by short- and long-lived radionuclides, temperature- and porosity-dependent parameters, compaction of porous material, and melting. In addition, B considers differentiation of a Fe core and silicate mantle by porous flow as well as magmatic heat transport and convection at melt fractions ≥50%, while A includes a genetic algorithm for parameter optimization. Our study proceeded in two steps. First, thermal evolution models that considered conductive heat transport, compaction and melting were calculated with A and compared to the thermo-chronological data in order to obtain an optimized parameter set. Using this parameter set, we then performed more detailed calculations with B that included melt migration.

Variable	Symbol	Unit	Value
fixed parameters			
Grain size	b	μm	0.2
Max. temp. Acapulco	$T_{A,max}$	K	1323
Initial porosity	ϕ_0		0.3
Initial $^{60}Fe/^{56}Fe$		10^{-8}	1.15
optimized parameters			
Formation time	t_0	Ma	1.68
Radius	R	km	263
Surface temperature	T_s	K	250
results			
Max. central temperature	$T_{c,max}$	K	1704
average burial depth			
Chondrule bearing acapulcoites		km	4.67
	T_{max}	K	1248
Acapulcoites		km	5.89
	T_{max}	K	1327
Lodranites		km	8.83
	T_{max}	K	1451

Table 2: Optimum fit parameters obtained with the model A and used to compute differentiation with the model B.

3. Results

The models were compared to the observed maximum metamorphic temperatures and thermo-chronological data available (Table 1). An optimized parameter set which fits to the data for the cooling histories of the meteorites was determined (Table 2). Since the obtained maximum temperatures were higher than the metal solidus, we calculated the differentiation of the optimum fit body. These calculations confirm the fits obtained and provide additional information about the interior structure of the parent body. These results indicate differentiation in the interior and small-scale melt migration at shallow depths. The resulting structure shows a fully differentiated metallic core and silicate mantle, a partially differentiated layer, and an undifferentiated shell that was once partially molten in its deeper part. The degree of differentiation of the burial layers derived is consistent with the meteoritic evidence.

4. Conclusions

Our results indicate a larger radius (≈270 km) and an earlier formation time (≈1.6 Ma) of the acapulcoite-lodranite parent body than typical estimates for ordinary chondrites' parent bodies (<130 km and >1.8 Ma[11]), consistent with a stronger thermal metamorphism. The optimum fit of the initial temperature of ≈250 K suggests a formation closer to the Sun as compared with the ordinary chondrites (≈180 K[11]). The burial depths of ≈7-11 km support excavation by a single impact event. The differentiated interior indicates that these meteorites could share a common parent body with some differentiated stony and iron meteorites.

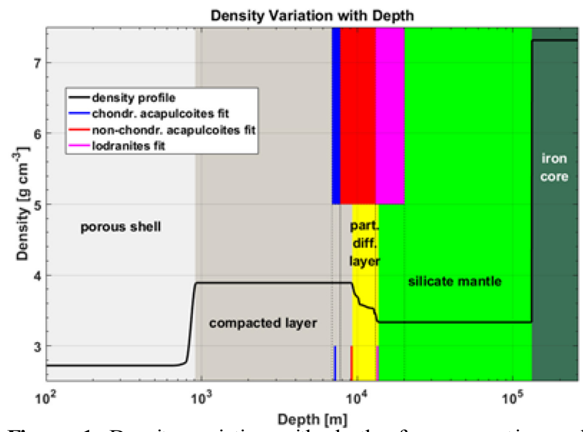

Figure 1: Density variation with depth after compaction and differentiation of the parent body. The unsintered shell (light grey) has a density of ≈2.7 g cm^{-3}, the layer at the depth of ≈1-9 km is compacted but not differentiated (dark grey) with a density of ≈3.9 g cm^{-3}. It is followed by an ≈4 km thick partially differentiated layer (yellow) where the density decreases to the mantle density of ≈3.3 g cm^{-3} due to iron depletion. The silicate mantle (light green) stretches to a depth of ≈132 km where the density jumps to ≈7.3 g cm^{-3} in the core (dark green). The layers that contain chondrule-bearing acapulcoites (blue), chondrule-free acapulcoites (red) and lodranites (pink) are indicated with the colors and dotted lines. The depths at which the data were fitted are indicated by the short lines with respective colors.

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Numerical SPIS-Dust Modelling of Plasma – Lunar Lander Interactions

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Abstract

One of the complicating factors of the future robotic and human lunar landing missions is the influence of the dust. Meteorites bombardment has accompanied by shock-explosive phenomena, disintegration and mix of the lunar soil in depth and on area simultaneously. As a consequence, the lunar soil has undergone melting, physical and chemical transformations.

Recently we have the some reemergence for interest of Moon investigation. The prospects in current century declare USA, China, India, and European Union. In Russia also prepare two missions: Luna-Glob and Luna-Resource. Not last part of investigation of Moon surface is reviewing the dust condition near the ground of landers. Studying the properties of lunar dust is important both for scientific purposes to investigation the lunar exosphere component and for the technical safety of lunar robotic and manned missions.

The absence of an atmosphere on the Moon's surface is leading to greater compaction and sintering. Proper-ties of regolith and dust particles (density, temperature, composition, etc.) as well as near-surface lunar exo-sphere depend on solar activity, lunar local time and position of the Moon relative to the Earth's magneto tail. Upper layers of regolith are an insulator, which is charging as a result of solar UV radiation and the constant bombardment of charged particles, creates a charge distribution on the surface of the moon: positive on the illuminated side and negative on the night side. Charge distribution depends on the local lunar time, latitude and the electrical properties of the regolith (the presence of water in the regolith can influence the local distribution of charge).

On the day side of Moon near surface layer there exists possibility formation dusty plasma system. Altitude of levitation is depending from size of dust particle and Moon latitude. The distribution dust particle by size and altitude has estimated with taking into account photoelectrons, electrons and ions of solar wind, solar emission. Dust analyzer instrument PmL for future Russian lender missions intends for investigation the dynamics of dusty plasma near lunar surface. PmL consists of three parts: Impact Sensor and two Electric Field Sensors.

One of the tools, which allows to simulate the dust emission from the Moon and asteroids, its transport, deposition and its interaction with a lander, is the SPIS-DUST (Spacecraft Plasma Interaction Software) code which based on Particle-in-Cell (PiC) method.

This paper presents first results of SPIS-DUST modelling of the interaction between the lunar plasma envi-ronment, regolith and a lander. The model takes into account the geometry of the Luna-Glob lander, the electric properties of materials used on the lander surface, as well as Luna-Glob landing place. Initial conditions were chosen based on the current theoretical models of formation of dusty plasma exosphere and levitating charged dust particles.

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