Planetary and Space Science 70 (2012) 20–27

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

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

Models of dust around Europa and Ganymede

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ARTICLE INFO

Article history:
Received 29 October 2010
Received in revised form
9 June 2012
Accepted 11 June 2012
Available online 18 June 2012

Keywords:
Dust
Cloud
Detection
Europa
Ganymede
Galileo
JUICE

ABSTRACT

We use numerical models, supported by our laboratory data, to predict the dust densities of ejecta outflux at any altitude within the Hill spheres of Europa and Ganymede. The ejecta are created by micrometeoroid bombardment and five different dust populations are investigated as sources of dust around the moons. The impacting dust flux (influx) causes the ejection of a certain amount of surface material (outflux). The outflux populates the space around the moons, where a part of the ejecta escapes and the rest falls back to the surface. These models were validated against existing Galileo DDS (Dust Detector System) data collected during Europa and Ganymede flybys. Uncertainties of the input parameters and their effects on the model outcome are also included. The results of this model are important for future missions to Europa and Ganymede, such as JUICE (JUpiter ICy moon Explorer), recently selected as ESA's next large space mission to be launched in 2022.

1. Introduction

Micrometeoroids (solid micron-sized dust particles) are a common constituent of the Solar System. They can easily reach the surfaces of atmosphereless bodies and, upon impact, cause the ejection of surface material into the surrounding space. The ejected dust fragments populate the space around the host bodies, where a part of the ejecta escapes and the rest eventually falls back to the surface. This process can be numerically modelled. In this paper we investigate dust around Europa and Ganymede created by micrometeoroid bombardment.

Our study is built upon the models developed by Krivov et al. (2003) and Krüger et al. (2003) supported by our impact experiments (Miljković et al., 2011) and hydrocode impact modelling to reduce the number of variables in the model. The impact experiments were made using the light gas gun (LGG) at the Open University's Hypervelocity Impact (HVI) laboratory (Miljković et al., 2011; Patel et al., 2010; McDonnell, 2006; Taylor et al., 2006). A series of high velocity impacts were made at 2 km s^{-1} using 1 mm diameter stainless steel balls as projectiles into pure water ice and sulphate hydrated mineral targets. The ejecta size (Miljković et al., 2011) and velocity distributions were measured and subsequently modelled using ANSYS AUTODYN finite element hydro-dynamic shock physics code (Miljković, 2010; Pierazzo et al., 2010).

The dust cloud model presented in this paper characterizes the dust environment (size, density, flux and velocity distribution of such dust) around Europa or Ganymede, predicts the dust densities of the ejecta outflux at any altitude within Europa's and Ganymede's Hill spheres (radius of 13,300 km or 8.5 R_E, where $R_E = 1565$ km for Europa and 32,000 km or 12 R_G, $R_G = 2631$ km for Ganymede) and can evaluate the dust density at any altitude as a function of the size distribution of the dust. We choose a discrete selection of altitudes and dust masses to give a representative set of results.

Our results are important for future space missions to Jupiter System that carry a dust detector onboard. This study can be further applied to estimate the dust counts into a dust detector in orbit around Europa and/or Ganymede. A dust detector has been proposed as part of a payload for a space mission to Europa and Ganymede. Initially named Laplace in 2007, it was renamed the Europa-Jupiter System Mission after ESA and NASA joined proposals in 2009 (Blanc et al., 2009) for a major mission to Jupiter System. In 2011, EJSM was reformed again into an ESA-led mission to Ganymede with flybys to Europa and Calisto, named JUICE (JUpiter ICy moon Explorer) (Dougherty et al., 2011). JUICE has recently been selected as ESA's next large mission for launch in 2022. If a dust detector is included in the payload, an in situ analysis of the dust that surrounds Europa and Ganymede will be possible, which could provide information about the surface, as its composition should be "written" in the detected dust (Miljković, 2011).

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0032-0633/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2012.06.006

The proposed dust detector should not only be capable of determining the density of dust in the cloud, but may provide chemical analysis of captured dust (Miljković et al., 2008), as was the case with the analysis of the Jovian Dust Stream particles by Cassini's CDA (Cosmic Dust Analyser) (Postberg et al., 2006). Chemical abundance maps of Europa and Ganymede even at low spatial mapping resolution show that water ice is non-uniformly distributed over the surfaces of Europa and Ganymede. The Galileo NIMS (Near Infra-red Mapping Spectrometer) spectra identified these impurities as hydrated minerals, sulphates and possibly hydrocarbons (McCord et al., 1998). As the surface material is ejected by micrometeoroid bombardment, it can be expected that the dust particles around Europa will be composed of water ice, sulphur salts and their decomposition products, including any potential organic compounds (Miljković, 2011). It should be emphasized that a dust detector has never visited Europa or Ganymede at such a close orbital distance or spent a longer time than in flybys. No chemical analysis of the dust in Jupiter System has been made yet, apart from Cassini's Cosmic Dust Analyser (CDA) measurements of the Io stream dust at more than 1 AU away from Jupiter (Postberg et al., 2006).

1.1. Comparison of the present dust cloud model with previous models

In previous work, Krivov et al. (2003) developed a spherically symmetric case for an atmosphereless body with applications to Ganymede and the Saturnian satellites to help the interpretation of Cassini's CDA (Cosmic Dust Analyser) measurements; Krüger et al. (2000) developed a dust cloud model around Ganymede to explain the Galileo DDS measurements; Sremčević et al. (2003) investigated the asymmetry of the dust clouds around Galilean and Saturnian satellites; Sremčević et al. (2005) compared the Galileo data with their models for Europa, Ganymede and Callisto, whereas Krüger et al. (2003) investigated the dust clouds around all four Galilean satellites.

The differences between the dust model presented here and that of Krüger et al. (2003) are the following: their slope of the cumulative ejecta mass distribution was approximated, whereas in our model our slope was derived directly from the impact experiments published in (Miljković et al., 2011). Krüger et al. (2003) reported that dust have mean mass of 10^{-11} g around Europa and 10^{-13} g around Ganymede, whereas in our model the ejecta fragment size distributions were calculated, and were in range between 10^{-15} and 10^{-7} g. Ejecta speed distributions in Krüger et al. (2003) were represented as the distribution of ejecta material having speeds higher than a certain speed that is dependent on the minimum ejecta speed of fragments and the power-law slope of the distribution, which were unknown variables fitted to match the Galileo data, whereas in our model, a size–velocity relation was applied to all the ejected fragments in order to have more precise outflux and spatial densities of ejected dust. We primarily focus on the short-lived, bound ejecta at a distance from the surface at which a spacecraft may orbit. Therefore, any asymmetry effects in the spatial density of ejected fragments caused by Europa's orbital motion can be excluded (such were considered by Sremčević et al., 2003) as well as the charging of dust fragments.

2. Micrometeoroid influx into Europa's and Ganymede's surface

In the Jovian system, there are five distinct sources of dust around Europa and Ganymede. These are (i) asteroidal and (ii) halo dust populations, as part of the interplanetary dust particle (IDP) population distinguished by their location and not necessarily by their origin (Divine, 1993); (iii) interstellar dust (ISD) that originate from beyond the Solar System; (iv) the Io stream and (v) ring dust that from the Jovian system itself.

2.1. Influx into Europa's and Ganymede's surface from the Solar System and interstellar region

Divine (1993) created a phase density model to predict micrometeoroid fluxes at different distances from the Sun. According to this model, there are five distinct interplanetary dust populations, out of which only two (asteroidal and halo) are present at Jupiter's orbital (heliocentric) distance, r. The cumulative number of IDPs per unit volume (spatial density, N_M) whose mass exceeds m can be calculated as a function of inclination, i, represented by elliptical latitude λ, eccentricity, e, and the IDP mass represented by H_m is shown in Eq. (1) (Divine, 1993).

$$N_M = \frac{1}{\pi}\int_0^{\infty} H_m\, dm \int_0^{\pi/2} N_1\, d\chi \int_{e_\chi}^{1} \frac{p_e\, de}{\sqrt{e-e_\chi}} \int_{|\lambda|}^{\pi-|\lambda|} \frac{p_i \sin i\, di}{\sqrt{(\cos\lambda)^2-(\cos i)^2}} \tag{1}$$

The mass distribution of micrometeoroids H_m is independent of the position and velocity of dust particles in the Solar System, the cumulative mass distribution of dust particles N_1 is a function of radial distance from the Sun; $\chi=\sin^{-1}(r_1/r)$ and $e_\chi=(r-r_1)/(r+r_1)$, where r_1 is the perihelion distance, r=5.2 AU and $\lambda=0^o$ are Jovian heliocentric distance and the equatorial latitude, p_e and p_i are normalized eccentricity and latitude distributions. Discrete values for N_1, H_m, p_e and p_i were taken from Divine (1993) for the respective asteroidal and halo populations and integrated in Eq. (1). H_m was integrated over mass bins (Δm), in order to transform the continuous mass distribution into a binned one:

$$N_M = const \int_m^{m+\Delta m} H_m\, dm \tag{2}$$

In newer meteoroid codes, the product of functions $N_1 x p_e x p_i$ is replaced by a single vector function, which provides a more accurate and detailed dust flux calculation (e.g. Dikarev et al., 2005). However, due to lack of observational data at 5 AU from the Sun, and since later meteoroid models were based on Divine (1993) (e.g. Jehn, 2000; Staubach et al., 1997), we consider the model by Divine (1993) to be satisfactory for a preliminary dust flux calculation at Jupiter's distance for dust coming from asteroidal and halo sources. It should be noted that we have neglected Solar radiation pressure due to Jupiter's large distance from the Sun.

Colwell and Horànyi (1996) calculated that at 100 R_J away from Jupiter, the Oort Cloud dust (highly inclined and eccentric dust associated with Divine's halo population) shown as triangles in Fig. 1 and planetary dust (low inclination and low eccentricity orbits, associated with Divine's asteroidal population) shown in squares in Fig. 1, move at a mean speed of 23.6 km s^{-1} and 6.6 km s^{-1}, respectively.

The interstellar dust (ISD) can be observed far above the equatorial plane. The Ulysses spacecraft monitored the ISD activity at high ecliptic latitudes between 3 and 5 AU from the Sun, which was far away from contamination by IPD (Grün et al., 1997). ISD penetrates the solar system at about 26 km s^{-1} (Landgraf et al., 2000; Krüger et al., 2007). Fig. 1 shows the ISD flux data taken by Ulysses spacecraft (that measured grain masses between 10^{-11} g and 10^{-7} g) and ground based radar meteor observations made by AMOR (Advanced Meteor Orbit Radar) facility, that measured the flux of ISD dust larger than 10^{-7} g. AMOR data in Fig. 1. is shown as a tail with a slope of -1.1