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Meteoroid environment on the transfer trajectories to Mars

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ABSTRACT

The possibility of meteoroid impact is one of the main threats to the interplanetary missions. Although the meteoroids in the interplanetary space have very small masses, their velocities are extremely large and can produce highly energetic impacts. In this paper, a specific method to analyze the meteoroid environment on the transfer trajectories to Mars has been developed, by determination of the closest approach situation for a large sample of meteoroid orbits. This allows to analyze, not only the integral flux of meteoroids on the spacecraft surfaces, but also the specific kinematics for every single approach and the distributions of important variables such as relative velocity and its projections on specific directions such as instantaneous directions to Mars, Earth, Sun and apex. The obtained results give the quantitative and qualitative estimate of these variables which are separated for different populations of interplanetary meteoroids. The most exposed parts of the spacecraft on the Hohmann transfer to Mars are directed toward Mars, apex and anti-Earth point while the Sun and anti-Sun directions are symmetrically threatened. This gives the frame for the mission design and impact risk assessment and for the development of mathematical models of the behavior of the new spacecraft protection materials under impact loading and also for their experimental examination.

1. Introduction

The case of Olympus spacecraft that experienced multiple anomalies on August 11, 1993, near the peak of the Perseid meteor shower emphasizes the importance of the investigation of the meteoroid and debris environment [4]. Another example is the Charge Coupled Devices (CCD) of XMM-Newton telescope which suffered at least 5 impact events during the first 6 years in orbit and one of these impacts permanently disabled a complete section of one CCD [8]. These are just some of the known cases which confirm that meteoroids and debris present serious threat to the operational spacecraft.

Number of space missions performed in situ measurements of the meteoroid environment in the vicinity of the Earth and deeper into the Solar system, such as Space Flyer Unit (SFU) which recorded over 700 hypervelocity impact signatures [23]. Depending on the size, velocity, and location of a meteoroid impact, there are various hazards to the operational spacecraft. The processes that have been observed on returned surfaces [5,1] are surface degradation, structural penetration and plasma discharge [24]. There are also other possible influences of the meteoroid (dust) environment on the spacecraft surfaces, such as so-called cold-spray phenomenon, which is characteristic of intermediate impact velocities [21].

Surface degradation occurs when the impacting meteoroid creates a crater in the spacecraft surface material which can change its optical and thermal properties and also reduce mechanical strength. On the other side, structural penetration presents the threat for pressurized containers which are part of almost every spacecraft as propellant tanks, gas storage of life support systems, etc. Because of the mass restrictions, these containers are usually designed only to support the internal pressure and if the impacting meteoroid has large kinetic energy, it can penetrate the container wall which will cause loss of pressure or a complete failure of the container's structure.

Another hazard, which is not explored enough, is the creation of a plasma cloud around the impact location. If the spacecraft is unevenly charged due to differences in the ultra-violet illumination from the Sun, the plasma created by the impact can create current between differently charged parts. This can make disturbances or destruction of the spacecraft electronic devices. There is speculation that the failure of Olympus spacecraft was the consequence of this mechanism [4]. Another problem that could arise from the high density of ions in the plasma cloud is the excessive current (short-circuiting) in the high-voltage instruments usually

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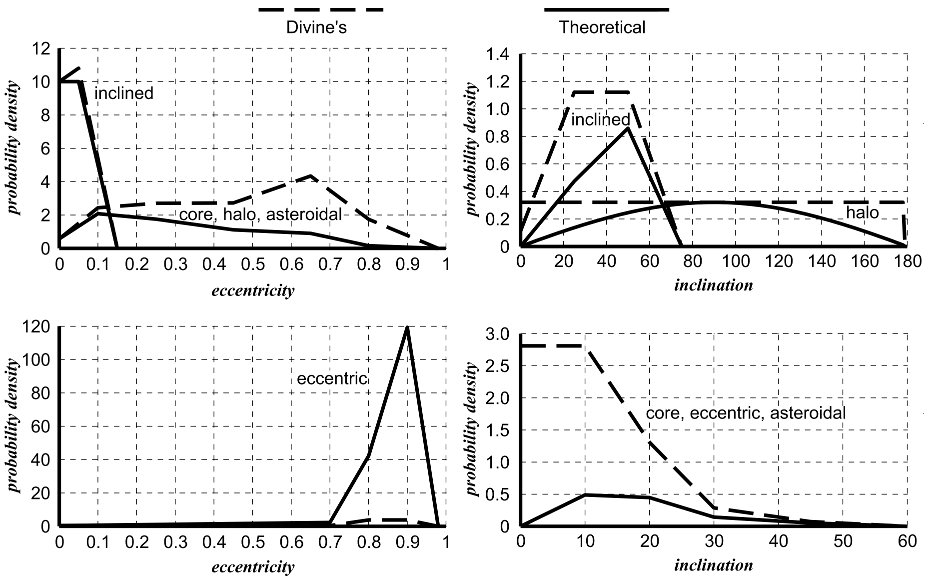

Fig. 1. Distributions of eccentricity and inclination of the Divine's populations.

used for detection of the charged particles, which can lead to the destruction of the instruments [24].

Number of models for predicting the damage from the meteoroids impact has been developed [9,29]. These models are based mostly on experimental procedures which give different semi-empirical equations for determination of the impact crater size, hole diameter, crack length etc. To avoid some of the damages or at least reduce the damages impact on the success of the mission, new kind of materials have being continuously developed. Recently, a lot effort has been invested in the research of functionally graded materials (FGM) introduced by Mitsue Koizumi [22]. Number of effective methods and theories to determine the static and dynamic behaviors of these structures under different kind of loads (e.g vibration, bending) has been developed [3,25]. Also, the response of these materials to high velocity impacts are under extensive research [13,27,29]. The increase in applications of these materials requires accurate mathematical models to predict their responses to meteoroid impact. The defining parameters for these models are analyzed in this paper (i.e. impact velocity, impact angle).

In this paper, the analysis of these parameters for the spacecraft on the interplanetary trajectory to Mars, based on the well-known Divine's interplanetary meteoroid model [7] and its reformulation [17] is presented. This model is very suitable for this kind of analysis since it defines separable distributions of the orbital elements for 5 meteoroid populations.

There are several important mechanisms which are responsible for the current state and evolution of the meteoroid environment in the Solar system. The most dominant are gravitational resonances [10] and non-gravitational mechanism such as Yarkovsky effect [28], Poynting–Robertson effect [20] and solar wind [19]. However, the Divine's interplanetary meteoroid environment model is based on the judgment that they may be less essential to a first-order meteoroid model. The approach adopted in this model incorporates the simplest dynamical model by assuming that the particles move in heliocentric orbits with solar gravitation as the only operative force.

The objective of this study is to determine the distributions of important parameters such as relative velocity at the closest approach and its projections on the important directions which can be references for orientation of the different spacecraft components such as communications, observational instrumentation, solar panels etc.

The main practical application of this work is determination of variables which are relevant for applying of the existing and development of new protection systems for the interplanetary spacecraft. Unlike the usual integral approach to this problem, by determination of flux of particles on oriented spacecraft surface, the approach presented here, based on Monte Carlo simulation, enables the deeper, both qualitative and quantitative insight into the meteoroid environment and the risk it present to the spacecraft on the specific transfer trajectories to Mars.

2. Interplanetary meteoroids models

Interplanetary flux model which has remained the standard for modeling the interplanetary meteoroid environment up to date was established in 1985 [15]. This model assumes the isotropic meteoroid distribution based on data from lunar crater counting, zodiacal light observation and in situ measurements by Pioneer 8 and 9, HEOS-2 and Helios spacecraft.

One of the first models which assumed non-isotropic distributions is the Divine's Interplanetary model [7]. This model divided interplanetary meteoroids into 5 populations – Core, Inclined, Eccentric, Halo and Asteroidal – each having separable distributions of particle mass, inclination, eccentricity and perihelion distance. However, this model needed reformulation in order to give the real theoretical distributions of the orbital elements [17].

In Fig. 1 the distributions of eccentricity and inclination for every population of the Divine's model are presented. We used this model because it is very suitable for this kind of analysis due to the separable distributions of orbital elements. This allows simple process of generation of the sample of the test orbits from the given distributions, as it is described in the following chapter.

The Divine's model was upgraded by using the data from the dust detectors on GALILEO and ULYSSES spacecraft [32]. In this model the solar radiation pressure was added as a perturbation force, and also Interstellar dust as additional population was introduced. Divine's model was also the basis for the development of METEM [11] model which is more suitable for analysis of the effect of the sporadic meteoroid environment. While all the mentioned models only fitted the observations without any consideration of physical effects responsible for the nature of the meteoroid environment, there are also models which try to implement these effects such as IMEM/Dikarev model [6].