



# 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.

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## 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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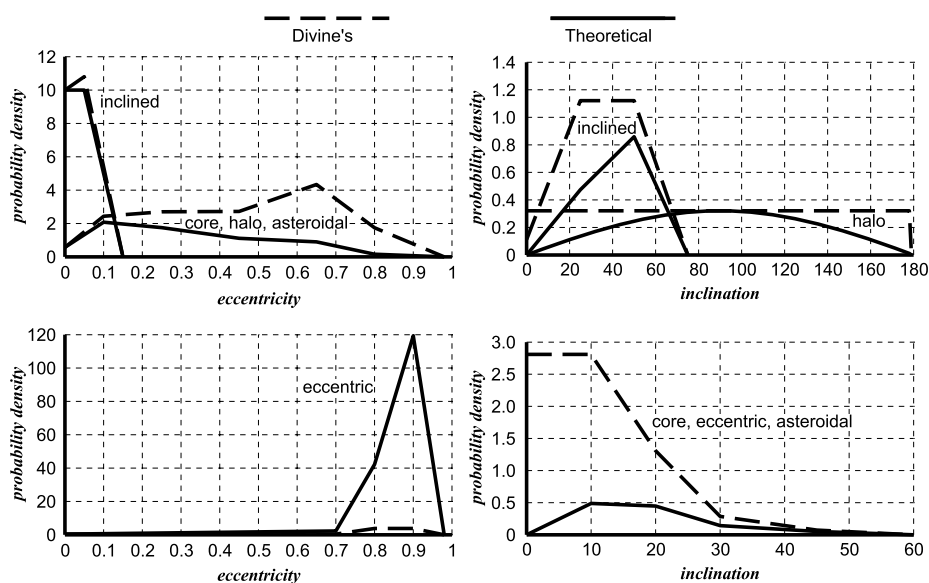


Fig. 1. Distributions of eccentricity and inclination of the Divine's populations.

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].

### 3. Analysis

In order to explore the geometry and kinematics of possible meteoroid impacts on the spacecraft on the transfer trajectory to Mars, a specific analysis has been performed by calculating the important impact parameters such as velocity, angle between the velocity vectors of the spacecraft and the meteoroid etc.

There has been many studies on the risk assessment on the operational spacecraft due to high-velocity impactors [31,12]. Unlike all these studies, which are based on the calculation of the integral flux of particles, the analysis presented here is based on individual approach to every particle in the sample which is generated from the available distributions of orbital elements. This approach enables specific kind of results, such as distributions of important variables (i.e. relative velocity, angle of approach relative to instantaneous directions of interest etc.). The practical significance of these results is the possibility to assess the most probable impact characteristics for any specific part of the spacecraft and population of the meteoroids. Because of this, the instantaneous direction of interest are chosen to correspond to real orientations of different spacecraft systems, such as communication system which is directed to the Earth, solar panels which are directed toward the Sun, observational instruments which can be directed toward the target of interest (in this case Mars) etc.

For the purpose of this analysis, a set of 5 million orbits, one million per each population of the Divine's interplanetary meteoroid model, was generated by Monte Carlo method. The transfer orbit is simple Hohmann transfer trajectory [16] starting at the Earth perihelion. Since all meteoroid populations have uniform distributions of longitude of the ascending node and argument of perihelion, there is no loss of generality by selecting any particular transfer orbit.

#### 3.1. Sample generation

An efficient algorithm, to generate the sample of orbits whose orbital elements follow the distributions given by the model, has been developed. This algorithm, based on the inverse transform sampling method, consists of four steps:

- Calculation of the cumulative distribution function by the integration of the probability density functions defined by the model with the piecewise functions, as it is presented in Fig. 1 for eccentricity and inclination.

$$F(x) = \int_{x_{min}}^x f(x) dx$$

where  $x$  is arbitrary orbital element.

- Calculation of the inverse cumulative distribution function (quantile function)

$$Q(p) = F(x)^{-1}$$

where  $p \in [0, 1]$  is the probability.

- Generation of the set  $E$  of the pseudorandom numbers with the uniform distribution on the interval  $[0, 1]$ .
- Calculation of the set of the values for the specific orbital element by assigning the value of the appropriate quantile function  $Q(p)$  to every member of the set  $E$ .

This algorithm was used to generate 5 million orbits (one million per each population) which satisfy the distributions of the orbital elements given by the model. In Fig. 2 these theoretical

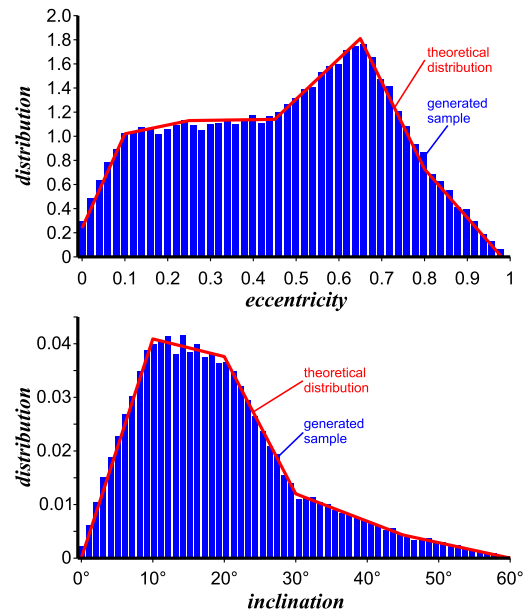


Fig. 2. Theoretical distributions and generated sample for Core population.

Table 1

Percentage of the selected orbits.

Population	%
Core	31.3
Inclined	42.9
Eccentric	40.9
Halo	0.035
Asteroidal	1.3

distributions for eccentricity and inclination (see Fig. 1) and normalized histograms of the generated sample for Core population are shown.

As it can be seen from Fig. 2, the generated sample of orbits matches Divine's distributions very well. Besides this, another limitation to the generated sample was implemented which enabled to analyze only those orbits whose perihelion distance is smaller than the aphelion distance of the transfer orbit and also the aphelion distance is larger than the perihelion distance of the transfer orbit. The fractions of orbits which satisfy these conditions are given in Table 1.

This limitation makes sure that, while the samples still satisfy the Divine's distributions, only the orbits that have the possibility to intersect the transfer orbit were analyzed while the irrelevant orbits, with too large perihelion or too small aphelion, are omitted.

#### 3.2. MOID determination

In order to determine the close approach kinematics, it is necessary to find the minimum orbit intersection distance (MOID) for every meteoroid orbit and velocities of the spacecraft and the meteoroid in the points corresponding to the MOID. There are number of methods to compute the MOID of the confocal elliptical orbits. Usually these methods allow determination of all critical points of the distant function between the orbits, which includes minimums, also called proximities among which the smallest one is the MOID, maximums and saddle points. There are three distinctive groups of these methods which rely on analytical, numerical and combined procedures [18,2,14,30]. For the purpose of this analysis, the combined analytical-numerical method was used [30]. The geometrical interpretation of this method is shown in Fig. 3.

This method was chosen because it is highly efficient and allows fast calculation for a large number of orbits which is suitable for this analysis. There are also other parameters important for this analysis such as longitude of the points corresponding to MOIDs, with respect to the ascending node for every meteoroid orbit, which are shown in Fig. 4 [26].

### 3.3. Closest approach kinematics

The closest approach interface between the spacecraft on the transfer trajectory to Mars and the meteoroid is presented in Fig. 5. In Fig. 5 all important features for this analysis, among which the most important are relative velocity vector and its projections

on the instantaneous directions toward Sun, Earth, Mars and apex are shown.

## 4. Results and discussion

As it is mentioned before, the most important parameters, regarding the risk for the operational spacecraft, are relative velocity and its projections on the important directions which are shown in Fig. 5. The distributions of relative velocities at the points of the closest approach for all 5 populations of the Divine’s model are shown in Fig. 6. All of the following distributions are calculated by cubic spline interpolation of the normalized histograms to obtain smooth density distributions which are expected from the extremely large number of meteoroids in the interplanetary space.

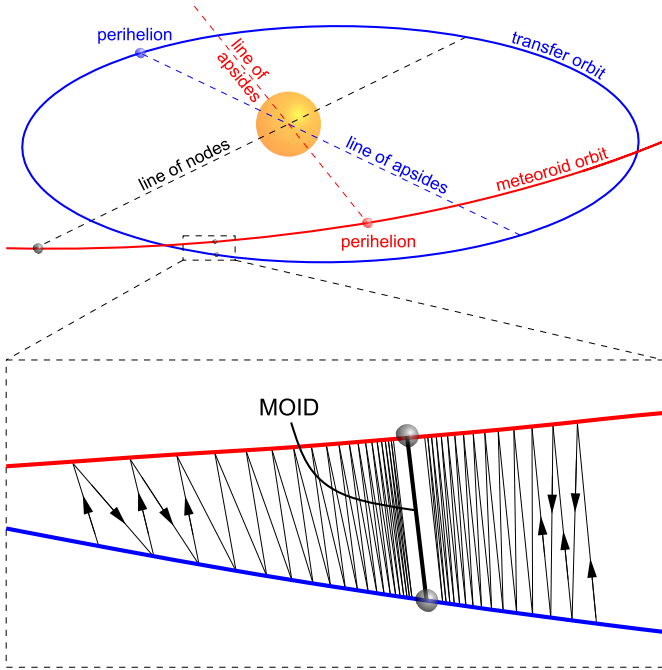


Fig. 3. Geometrical interpretation of the method for the MOID determination.

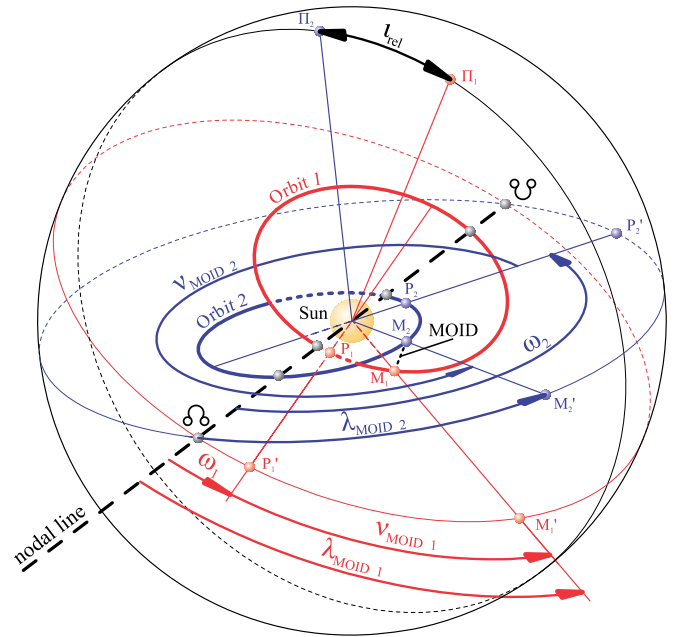


Fig. 4. Geometry of the confocal elliptical orbits.

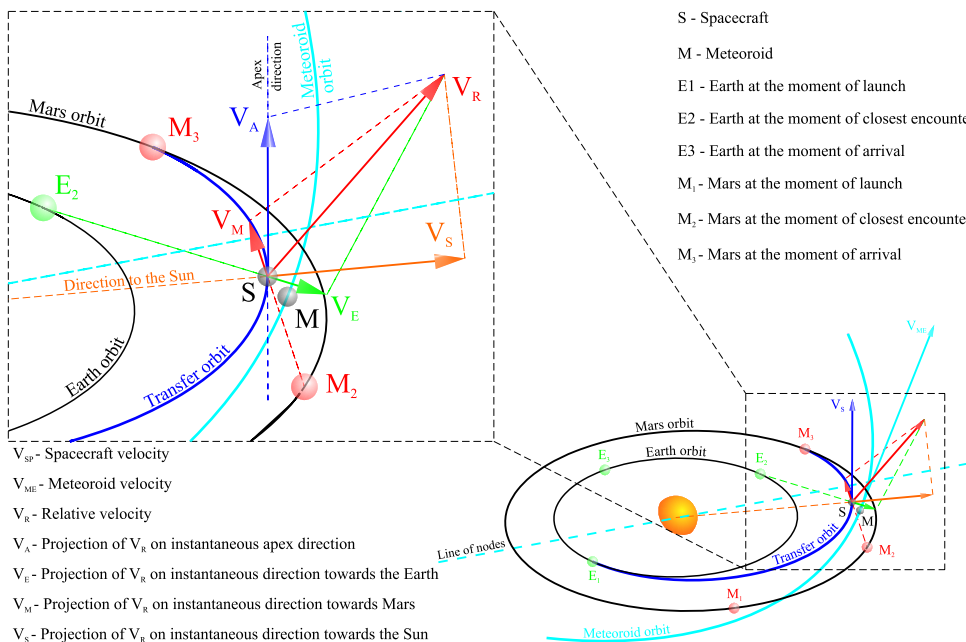


Fig. 5. Closest approach kinematics.

In Fig. 6 one can see that the relative velocities for all populations are distributed over the similar domain and are relatively symmetric but have large differences in the mode value. The most distinctive case is Halo population having most probable value of about 30 km/s.

In Fig. 7 the distributions of projections of the relative velocity ( $V_R$ ) on the instantaneous directions toward the apex, Mars, Earth and Sun are shown. Negative values of the velocity projections mean the approach from the direction of the specified point (Sun, Earth, Mars or apex point), while the positive values mean the approach from the opposite direction.

Fig. 7 shows that for all 5 populations majority of the distribution of the projections of relative velocity ( $V_R$ ) on the apex direction ( $V_A$ ) is in the negative part of the domain meaning that

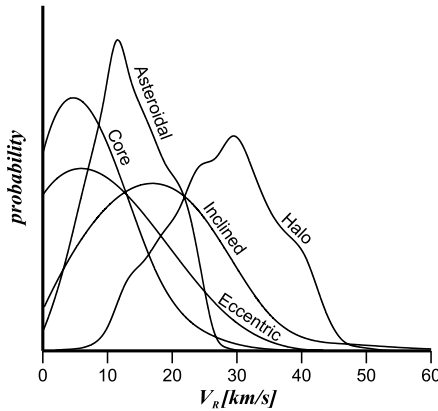


Fig. 6. Distributions of relative velocities.

the parts of the spacecraft which face the apex direction are more exposed to the possible impacts. This is especially true for Halo population due to the large number of meteoroids on highly inclined and retrograde orbits.

Similar situation is with projection of the relative velocity ( $V_R$ ) on the instantaneous direction to Mars ( $V_M$ ). All populations except Asteroidal has major part in the negative part of the domain meaning that the parts of the spacecraft facing toward Mars are more exposed to possible impacts than the opposite parts.

On the other hand, the situation with the projection of the relative velocity ( $V_R$ ) on the instantaneous direction to the Earth ( $V_E$ ) is opposite from the previous two. Most of the approaches come from the vicinity of the “anti-Earth” point.

Unlike the previous cases, the distributions of the projections of ( $V_R$ ) on the instantaneous direction toward the Sun ( $V_S$ ) are quite symmetric with respect to 0 value indicating that there is similar possibility of the impact from the Sun and “anti-Sun” position.

Since the collision between the spacecraft and meteoroid can occur only at one of the nodes, it is necessary to explore the locations of the points corresponding to MOIDs in order to see if the closest approach can be used as a relevant representative of the true collisions. For this purpose, the longitudes of the points corresponding to MOIDs with respect to ascending node of every meteoroid orbit (see Fig. 4) are calculated and presented in Fig. 8 (ordinate for Inclined population is scaled 5 times with respect to other 4 populations).

In Fig. 8, one can see that these distributions have peaks in the vicinity of the nodes which are particularly sharp for more inclined orbits of Inclined population. These distributions are symmetric since there is no reason for one of the nodes to be favored in this case.

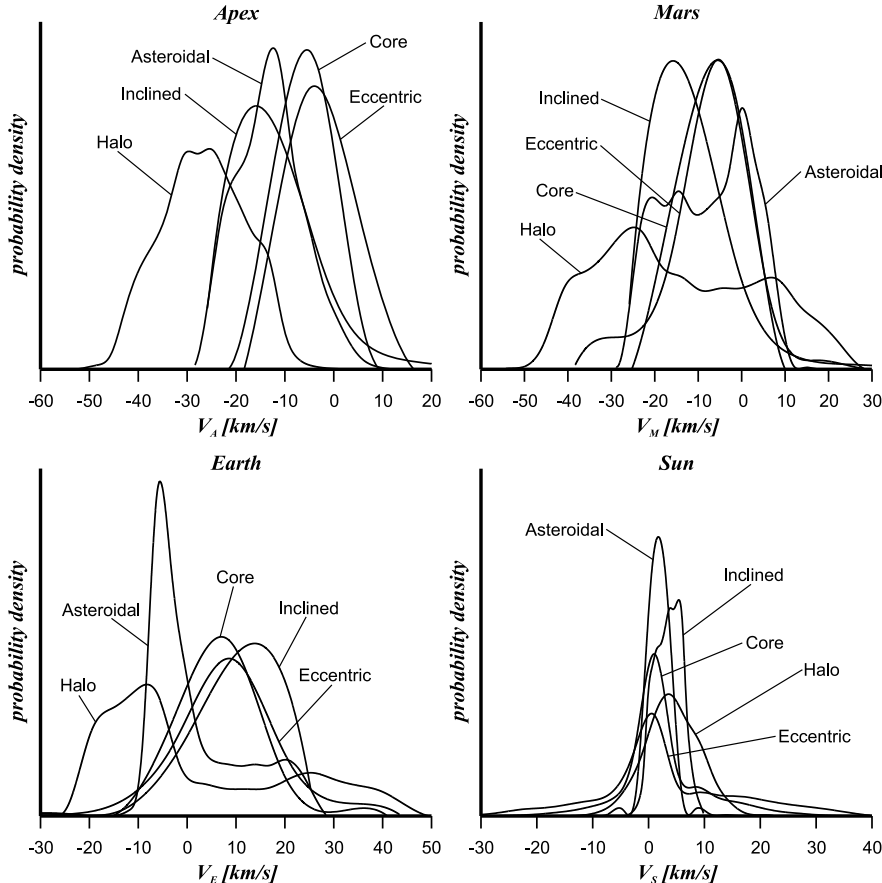


Fig. 7. Distributions of projections of the relative velocities.

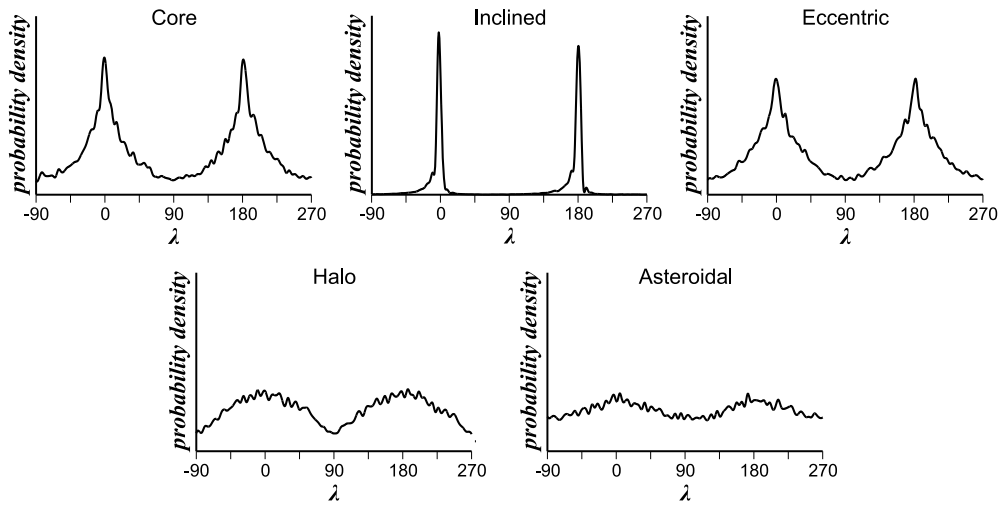


Fig. 8. Longitudes of the points corresponding to the MOIDs.

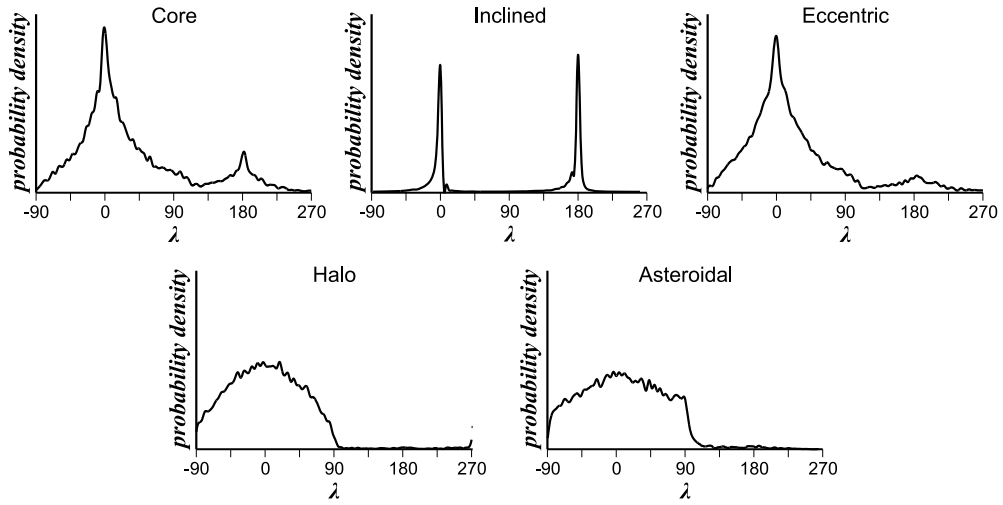


Fig. 9. Longitudes of the points corresponding to the MOIDs with respect to the node closer to the perihelion.

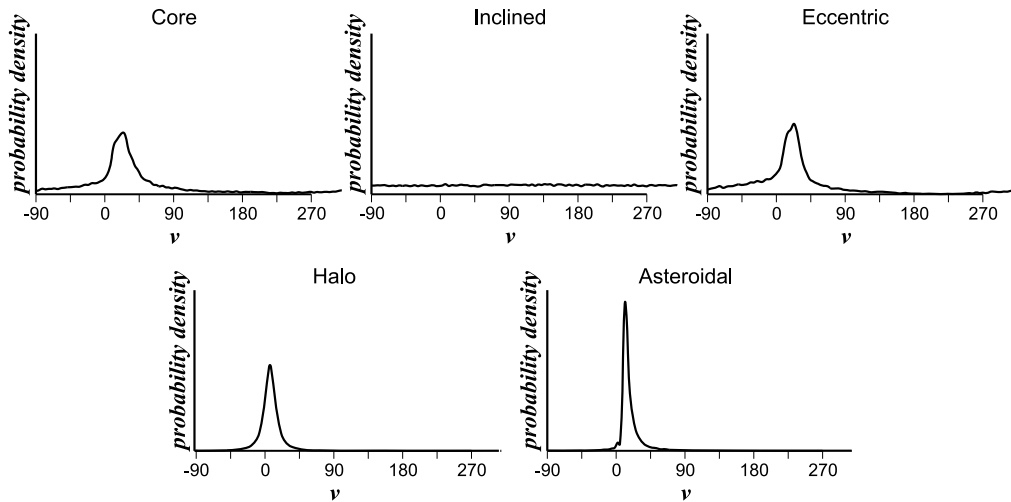


Fig. 10. True anomalies of the points corresponding to the MOIDs.



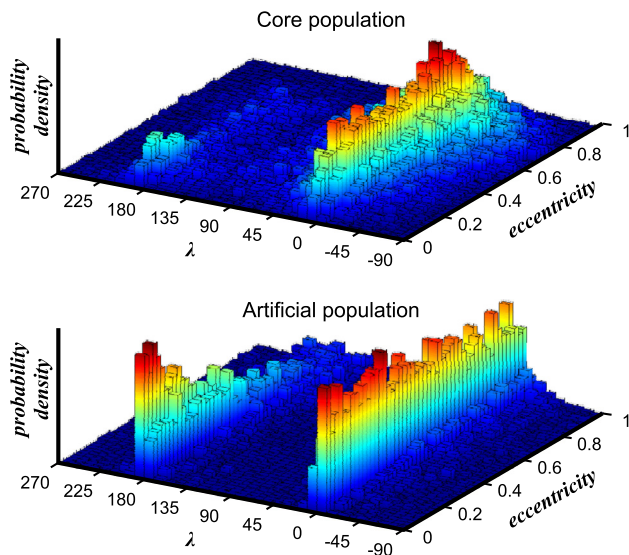


Fig. 11. Bivariate distributions for Core and the artificial population.

However, when the longitudes are calculated, not with respect to the ascending node as in the previous case, but with respect to the node which is closer to the perihelion of meteoroid orbit, the situation is completely different, as it can be seen in Fig. 9 (ordinate for Inclined population is scaled 5 times with respect to other 4 populations).

In Fig. 9 one can see that there is a large concentration of the points of the closest approach in the vicinity of the node which is closer to the perihelion. This can also be seen in Fig. 10 where the distributions of true anomalies of these points are shown.

In Fig. 10, one can see that Inclined population is the exception from the other populations having nearly uniform distribution of the true anomalies. In order to explore if this phenomenon is a consequence of specific combination of distributions of Keplerian elements or just a consequence of the fact that all orbits of Inclined population are low eccentric (see Fig. 1), a new set of one million orbits with uniform distribution of perihelion distance, eccentricity, inclination, longitude of ascending node and argument of perihelion was synthesized using the same method as previously described.

In Fig. 11 normalized bivariate distributions for Core and this artificial population are shown.

In Fig. 11 one can see that for both populations there is concentration of the points corresponding to MOIDs in the vicinity of the node closer to the perihelion. Also it can be seen that concentration of these points in the vicinity of the other node appears only for low eccentric orbits where the distribution is quite symmetric, which coincide with uniform distribution of the true anomalies for Inclined population shown in Fig. 10.

## 5. Conclusions

From the above analysis several conclusions can be drawn:

- Analyzed populations have very different distributions of the velocities at the points of closest approach and thus in the case of possible collisions.
- Parts of the spacecraft directed toward the apex and Mars are more exposed to the possible impacts than the opposite sides. The exception is Asteroidal population for which “anti-Mars” direction is dominant.
- The situation with the instantaneous direction toward the Earth is opposed from that of Mars except for Halo population. Generally, all presented distributions for Halo population

are very different from other 4 populations. This is obviously due to equal number of prograde and retrograde orbits in Halo population.

- Sun and “anti-Sun” directions are relatively symmetrically exposed to possible impacts.
- There is a large concentration of the points corresponding to MOIDs in the vicinity of the perihelia of meteoroid orbits. This is particularly true for highly eccentric orbits meaning that these meteoroids are the most dangerous due to high velocities in the vicinity of the perihelia. This is the most important conclusion from this analysis which can have impact on the general analysis of the collisions in the Solar system.

## Conflict of interest statement

None declared.

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