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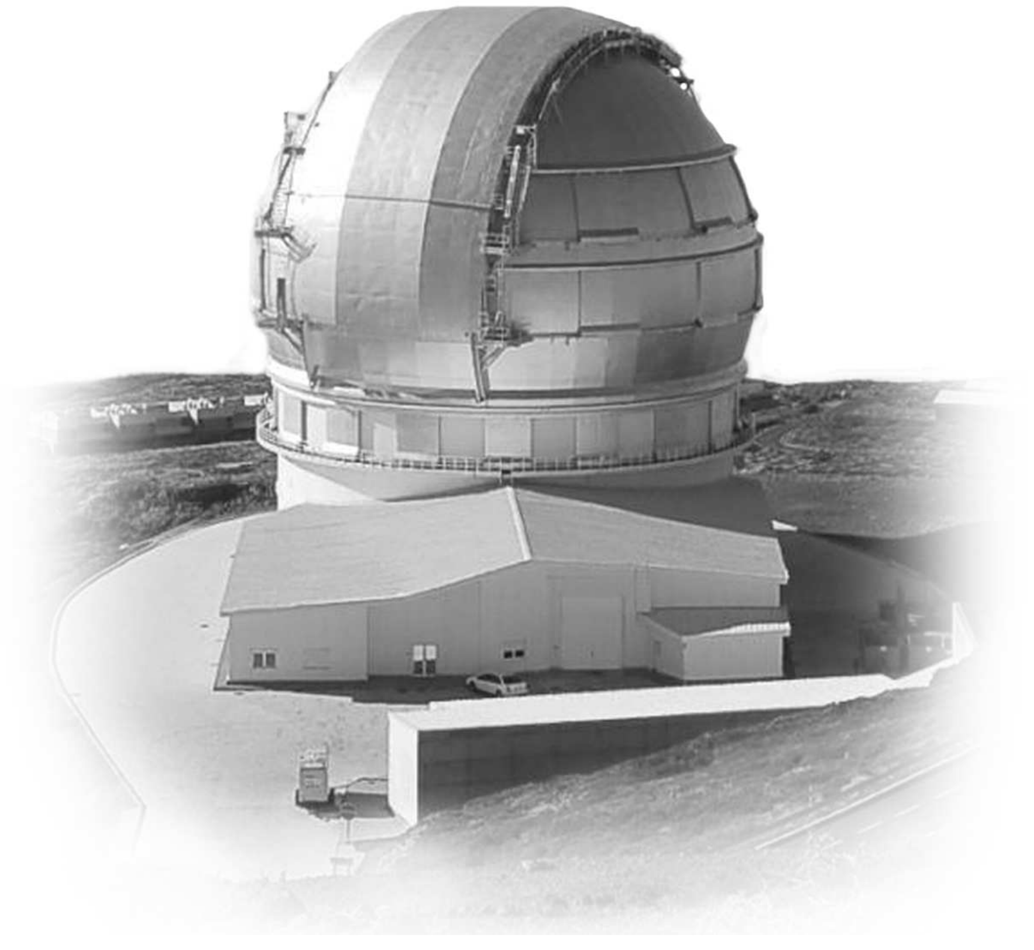

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# Collisions of small bodies as a source of hyperbolic meteoroids in the Solar System

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We present the results of the investigation of one possible mechanism which can be the source of meteoroids with hyperbolic orbital velocities: the mutual collisions of Oort Cloud objects, Kuiper Belt objects, or Main Belt asteroids, or their collisions with other populations of small bodies in the Solar System. In our study, we used model orbits for Oort cloud objects, Classical Kuiper Belt objects and Main Belt asteroids with different semi-major axes, and studied the orbital behavior of their fragments after their collision with other small bodies, e.g., bodies on orbits similar to those of Kreutz cometary family. Depending on their direction, the fragments will migrate into the inner or outer part of the Solar System, with different orbital velocities.



## 1 Introduction

The Solar System is being crossed by meteoroids with different orbital velocity. Part of them move on orbits with eccentricity higher than 1. These so-called hyperbolic meteoroids either have their origin within the Solar System or outside. In both cases, such high-speed meteoroids may originate from similar causes, which we know in our own Solar System. Generally speaking, these causes are cometary activity, mutual collisions of small bodies, eruptions from satellites of the planets, and consequent gravitational and non-gravitational forces (e.g., Kazantsev and Sherbaum, 1990; Kolomiyets, 2002).

The present study deals with the analysis of one possible source of hyperbolic meteoroids, namely mutual collisions of small bodies in the Solar System. The effect of such collisions will be most noticeable within the three regions in the Solar System where the spatial density of small bodies is much higher than in the other regions: the Main Belt, the Kuiper Belt, and the Oort Cloud. Therefore, this study will focus on collisions in these regions.

Our knowledge about these regions is not very old. The first asteroid discovery, Ceres, from the Main Belt, was by Giuseppe Piazzi, on January 1, 1801. The Oort Cloud was postulated by Ernst Öpik in 1932. This idea was independently revised by Jan H. Oort in 1950. The existence of trans-Neptunian objects was first suggested by Frederick C. Leonard in 1930. This hypothesis was revived by Kenneth Edgeworth in 1943 and Gerard Kuiper speculated about a similar disk in 1951.

Within the last two decades, numerous small bodies have been located in the region of the Solar System beyond that of the planets, extending from the orbit of Neptune (at 30 AU) to approximately 50 AU from the Sun, in the Kuiper Belt. Astronomers categorized them into several populations according to their physical and dynamical parameters. One of these populations, the "Classical Kuiper Belt" object, contains bodies with diameters in the order of 100–1000 km and less. The population is characterized by the orbits of its objects. These orbits resemble the orbits of the planets, nearly circular with an eccentricity of less than 0.1, and with a relatively low inclination up to about 10° (e.g., Bernstein et al., 2004; Morbidelli, 2004; Gomes et al., 2005; Delsanti and Jewitt, 2006).

During the existence of the Solar System, the bodies in the Kuiper Belt underwent various physical processes, including collisions (e.g., Stern, 2003). The observational evidence for collisions between Kuiper Belt objects is quite strong. Collisions in the Kuiper Belt can have a wide range of effects on the Belt's structure. The current root mean square velocity in the Kuiper belt is about 1.5 km/s. In case of a collision, such a velocity is sufficient to disrupt catastrophically the objects involved and/or to change their orbital velocity (Gurnett et al., 1997; Humes, 1980; Jewitt and Luu, 2000; Leinhardt et al., 2007). The effect of the mutual collision depends on the masses of the colliding bodies, the collision velocity, and the direction.

The present authors (2009) offered one possible mechanism that may cause the migration of objects from the Kuiper Belt—collisions with small bodies. A target object, receiving impulse in the tangential component of the orbital velocity near the aphelion, can be transferred to the inner or outer part of the Solar System, depending on direction and magnitude of the impulse.

Similar disruptive effects are possible in the Main Asteroid Belt and the Oort Cloud. In all cases, numerous small fragments are created by the collision. Their orbital dynamics is similar to the dynamics of large fragments; only their orbital velocity will be higher. Fragments will migrate into the inner or outer part of the solar system depending on their orbital velocity.

## 2 Model orbits

To investigate the collisional possibilities, we considered a target body of mass $m_1 = 10^{12}$ kg and an impactor with similar mass $m_2$. It is well-known that the collision would be effective with regard to changing the orbital velocity if the momenta of motion of the colliding bodies were comparable.

In the investigated regions, the Main Belt, the Kuiper Belt, and the Oort Cloud, we took similar steps for the calculation of the final orbits from the initial ones. As the initial model orbit, we selected circular orbits and orbits with an eccentricity $e = 0.2$, and with semi-major axes of 3.3, 50, and 50 000 AU, which correspond to the outer edges of the regions.

The simplification the put the initial inclination at $i = 0°$, to get the results in a clearer graphical form, does not affect the general conclusions. The bodies with such orbits are Earth crossers not only with the nodes. The starting epoch for the planets and the initial orbit is January 1, 2001. The model variant on the initial orbits is defined by the initial orbits whose tangential and radial component of the orbital velocity were changed by a value of $\Delta v_t$ and/or $\Delta v_r$.

Figure 1 shows a schematic distribution of an initial circular orbit with a semi-major axis $a = 3.3$ AU in the ecliptic plane and its model variants for the changes in orbital velocity by about $\Delta v$ in the heliocentric coordinate system. The orbits of the planets are projected onto the ecliptic plane. Table 1 contains the values for the changes in orbital velocity.

Similar orbit modelings from the initial circular one with $a = 50$ AU and $a = 50\,000$ AU are plotted in Figures 2 and 3, respectively. The corresponding tables with the changes in orbital velocity are Tables 2 and 3, respectively.

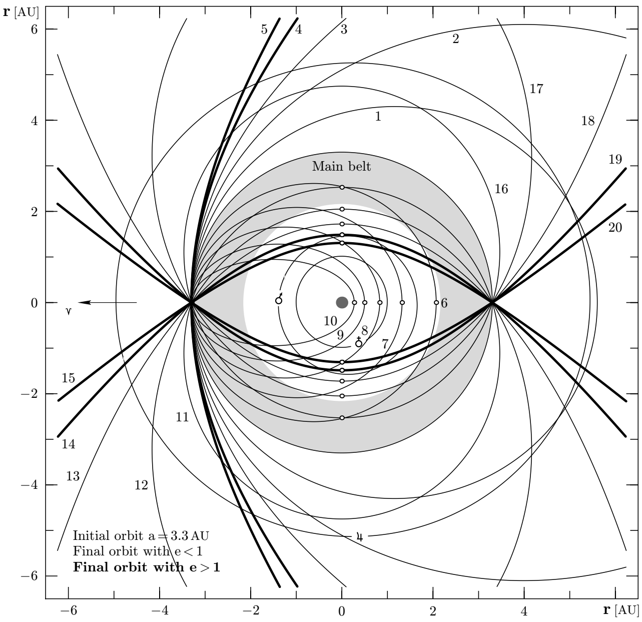


*Figure 1* – Initial orbit ($a = 3.3$ AU, $e = 0$, $i = 0°$) and final orbits after changing the orbital velocity by $\Delta v$. Values of $\Delta v$ can be found in Table 1.

*Table 1* – Tangential $\Delta v_t$ and radial $\Delta v_r$ velocity added to the Main Belt's initial circular orbit with $a = 3.3$ AU.

| No. | $\Delta v_t$ | $\Delta v_r$ |
|---|---|---|
| 1 | + 2 km/s | 0 km/s |
| 2 | + 4 km/s | 0 km/s |
| 3 | + 6 km/s | 0 km/s |
| 4 | + 8 km/s | 0 km/s |
| 5 | +10 km/s | 0 km/s |
| 6 | − 2 km/s | 0 km/s |
| 7 | − 4 km/s | 0 km/s |
| 8 | − 6 km/s | 0 km/s |
| 9 | − 8 km/s | 0 km/s |
| 10 | −10 km/s | 0 km/s |
| 11 | 0 km/s | + 5 km/s |
| 12 | 0 km/s | +10 km/s |
| 13 | 0 km/s | +15 km/s |
| 14 | 0 km/s | +20 km/s |
| 15 | 0 km/s | +25 km/s |
| 16 | 0 km/s | − 5 km/s |
| 17 | 0 km/s | −10 km/s |
| 18 | 0 km/s | −15 km/s |
| 19 | 0 km/s | −20 km/s |
| 20 | 0 km/s | −25 km/s |

## 3 Earth crossers' hyperbolic orbits

The hyperbolic orbits from the previous section do not approach the vicinity of the Earth. Bodies on such orbits migrate to the outer part of the Solar System, and ultimately become interstellar objects. However, they are not typical products of collisions, because only one component of their orbital velocity was changed. In our flat model, it is much more likely that the collision changed both components of the orbital velocity.

An example of such a model is shown in Figure 4, with changes in both the tangential and radial components of the orbital velocity. The values of the changes in the velocity components are given in Table 4. In this case, we used two initial orbits typical for each of the regions, the initial circular orbit and the initial elliptical orbit with eccentricity $e = 0.2$.

## 4 Earth crossers' parabolic orbits

A lot of fragments in a collision can change their initial orbits to parabolic or near-parabolic ones, and end up in the Sun. Much more smaller changes of the initial

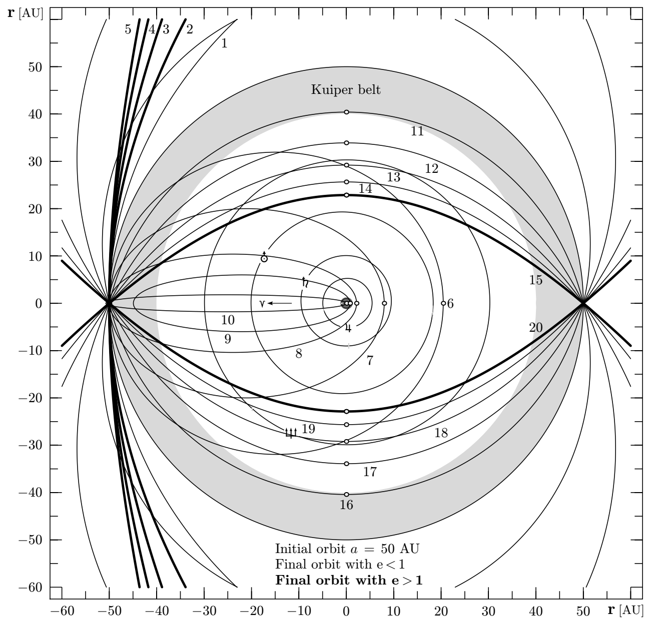


*Figure 2* – Initial orbit ($a = 50$ AU, $e = 0$, $i = 0°$) and final orbits after changing the orbital velocity $\Delta v$. Values of $\Delta v$ can be found in Table 2.

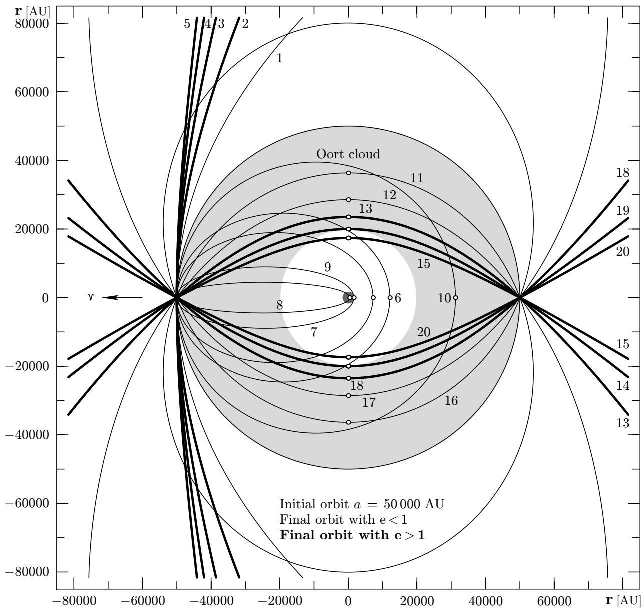


*Figure 3* – Initial orbit ($a = 50\,000$ AU, $e = 0$, $i = 0°$) and final orbits after changing the orbital velocity by $\Delta v$. Values of $\Delta v$ can be found in Table 3.

*Table 2* – Tangential $\Delta v_t$ and radial $\Delta v_r$ velocity added to the Kuiper Belt's initial circular orbit with $a = 50$ AU.

| No. | $\Delta v_t$ | $\Delta v_r$ |
|---|---|---|
| 1 | +1 km/s | 0 km/s |
| 2 | +2 km/s | 0 km/s |
| 3 | +3 km/s | 0 km/s |
| 4 | +4 km/s | 0 km/s |
| 5 | +5 km/s | 0 km/s |
| 6 | −1 km/s | 0 km/s |
| 7 | −2 km/s | 0 km/s |
| 8 | −3 km/s | 0 km/s |
| 9 | −4 km/s | 0 km/s |
| 10 | −5 km/s | 0 km/s |
| 11 | 0 km/s | +1 km/s |
| 12 | 0 km/s | +2 km/s |
| 13 | 0 km/s | +3 km/s |
| 14 | 0 km/s | +4 km/s |
| 15 | 0 km/s | +5 km/s |
| 16 | 0 km/s | −1 km/s |
| 17 | 0 km/s | −2 km/s |
| 18 | 0 km/s | −3 km/s |
| 19 | 0 km/s | −4 km/s |
| 20 | 0 km/s | −5 km/s |

*Table 3* – Tangential $\Delta v_t$ and radial $\Delta v_r$ velocity added to the Main Belt's initial circular orbit with $a = 50\,000$ AU.

| No. | $\Delta v_t$ | $\Delta v_r$ |
|---|---|---|
| 1 | +0.05 km/s | 0 km/s |
| 2 | +0.10 km/s | 0 km/s |
| 3 | +0.15 km/s | 0 km/s |
| 4 | +0.20 km/s | 0 km/s |
| 5 | +0.25 km/s | 0 km/s |
| 6 | −0.05 km/s | 0 km/s |
| 7 | −0.10 km/s | 0 km/s |
| 8 | −0.15 km/s | 0 km/s |
| 9 | −0.20 km/s | 0 km/s |
| 10 | −0.25 km/s | 0 km/s |
| 11 | 0 km/s | +0.05 km/s |
| 12 | 0 km/s | +0.10 km/s |
| 13 | 0 km/s | +0.15 km/s |
| 14 | 0 km/s | +0.20 km/s |
| 15 | 0 km/s | +0.25 km/s |
| 16 | 0 km/s | −0.05 km/s |
| 17 | 0 km/s | −0.10 km/s |
| 18 | 0 km/s | −0.15 km/s |
| 19 | 0 km/s | −0.20 km/s |
| 20 | 0 km/s | −0.25 km/s |

orbital velocity are needed for the creation of such type of orbits than for the case of hyperbolic orbits. It is sufficient to shift the value of the tangential component of the initial orbit to a value close to zero. For the Main Belt initial orbits, the added velocity is $\Delta v_t \approx -16$ km/s, for the Kuiper Belt orbits $\Delta v_t \approx -4$ km/s, and for the Oort Cloud orbits $\Delta v_t \approx -0.1$ km/s.

Some of these fragments can have close encounters with planets. In this case, their orbits get changed by planetary perturbations to another type of orbit, e.g., long-periodic or hyperbolic orbits.

## 5 Conclusion

Mutual collisions between Main Belt, Kuiper Belt, or Oort Cloud bodies, or collisions with small bodies on highly eccentric orbits, e.g., long-periodic and aperiodic comets on low-inclination orbits, could lead to a variety of events that would take place over a period of many years.

Collisions in these regions would produce many fragments that could drift in many different directions away from the explosion. A few fragments could be captured

*Table 4* – Hyperbolic orbits calculated from initial orbits by changing their orbital velocity in the aphelion.

| No. | Initial orbit | | $\Delta v_{\mathrm{r}}$ | $\Delta v_{\mathrm{t}}$ | Final orbit | | |
|---|---|---|---|---|---|---|---|
| | $q$ | $e$ | | | $q$ | $e$ | $\omega$ |
| 1 | 3.3 AU | 0 | +20.00 km/s | −4.16 km/s | 0.91 AU | 1.01 | 244° |
| 2 | 3.3 AU | 0 | −20.00 km/s | −4.16 km/s | 0.91 AU | 1.01 | 116° |
| 3 | 50 AU | 0 | +10.00 km/s | −3.64 km/s | 0.46 AU | 1.03 | 198° |
| 4 | 50 AU | 0 | −10.00 km/s | −3.64 km/s | 0.46 AU | 1.03 | 162° |
| 5 | 50 000 AU | 0 | + 7.00 km/s | −1.32 km/s | 0.80 AU | 1.04 | 197° |
| 6 | 50 000 AU | 0 | − 7.00 km/s | −1.32 km/s | 0.80 AU | 1.04 | 163° |
| 7 | 3.3 AU | 0.2 | +20.00 km/s | −5.19 km/s | 0.99 AU | 1.03 | 248° |
| 8 | 3.3 AU | 0.2 | −20.00 km/s | −5.19 km/s | 0.99 AU | 1.03 | 113° |
| 9 | 50 AU | 0.2 | +10.00 km/s | −3.98 km/s | 0.55 AU | 1.04 | 200° |
| 10 | 50 AU | 0.2 | −10.00 km/s | −3.98 km/s | 0.55 AU | 1.04 | 160° |
| 11 | 50 000 AU | 0.2 | + 7.00 km/s | −1.45 km/s | 0.81 AU | 1.05 | 197° |
| 12 | 50 000 AU | 0.2 | − 7.00 km/s | −1.45 km/s | 0.81 AU | 1.05 | 163° |

*Table 5* – Values of orbital velocities in the Main Belt, the Kuiper Belt, and the Oort Cloud. We refer to the text for more explanations.

| $a$ | $v_{\mathrm{circ}}$ | $v_{\mathrm{par}}$ | $\Delta v_{\text{E-hyp}}$ | $\Delta v_{\text{E-par}}$ | $\Delta v_{\mathrm{hyp}}$ |
|---|---|---|---|---|---|
| 3.3 AU | 16 km/s | 23 km/s | 20 km/s | −16 km/s | > 3 km/s |
| 50 AU | 4 km/s | 6 km/s | 10 km/s | − 4 km/s | > 1 km/s |
| 50 000 AU | 0.1 km/s | 0.2 km/s | 7 km/s | − 0.1 km/s | > 0.1 km/s |

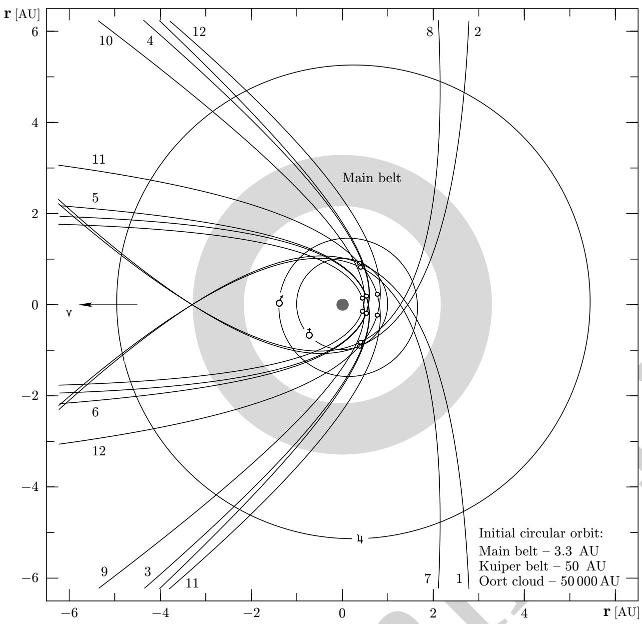


*Figure 4* – Hyperbolic orbits with the perihelium inside the Earth's orbit calculated from initial orbits with eccentricity $e = 0$ and $e = 0.2$. For the orbital parameters, see Table 4.

into an orbit around a planet. The collisions could result in a change of the components of the orbital velocity and modify the initial orbits to orbits with different perihelion and aphelion distances, different eccentricities, and inclinations.

Some small fragments are shifted on hyperbolic orbits, and migrate out of the Solar System as hyperbolic meteoroids. Part of them can cross the inner part of the Solar System. In the case they cross the Earth's orbit, they can be observed as hyperbolic meteors.

Table 5 contains the values of the orbital velocities from which we can deduce the possible creation of hyperbolic or parabolic orbits by collision events within the regions (in our model, the heliocentric distance of the Main belt, $a = 3.3$ AU, the Kuiper belt, $a = 50$ AU, and the Oort cloud, $a = 50\,000$ AU. In Table 5, $v_{\mathrm{circ}}$ and $v_{\mathrm{par}}$ are the circular and parabolic orbital velocity for the corresponding heliocentric distance, and $\Delta v_{\text{E-hyp}}$ and $\Delta v_{\text{E-par}}$ are the velocities required to change the initial velocity of a model orbit with for the creation of hyperbolic, respectively parabolic, orbits which cross the Earth's orbit. Finally, $\Delta v_{\mathrm{hyp}}$ is the velocity required to change the initial velocity with for the creation of a hyperbolic orbit which is not crossing the Earth's orbit. The collisions among the Main Belt bodies can produce all types of orbits, from elliptical up to the Earth-crossing hyperbolic orbits. Within the Kuiper Belt and the Oort Cloud, they can only produce elliptical and parabolic Earth-crossing orbits, as well as hyperbolic non-Earth-crossing orbits.

The collisions between small bodies which move in the Solar System on long-period or parabolic orbits and bodies from all three investigated regions can produce all types of orbits. In general, the creation of orbits of fragments after a collision is more complicated. The orbits are affected by planetary gravitational perturbations at close encounters. Moreover, small fragments suffer the influence of non-gravitational forces.

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