Comparison of different methods for preventive destruction of a hazardous asteroid

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Abstract. This paper deals with one of the methods asteroid hazard mitigation. The preventive destruction of a hazardous asteroid during the previous close encounter before its predicted collision is considered. Two variants of the explosion are considered: in the first case a projectile overtakes an asteroid; in the second one the situation is contrary. The second way requires significantly lower velocity of spacecraft delivery. On the other hand, it loses to the first way, since the number of fragments falling to the Earth is about an order of magnitude larger. However, with a more careful approach (non-isotropic explosion), this unfavorable factor can be likely reduced.

1. Introduction

Asteroid threat is very important problem [1–5]. Up to now many methods to mitigate the asteroidal hazard are proposed. The most radical one is the destruction of the object by its explosion [6-8]. In this case the main problem is to estimate the danger arising from the possible fall of fragments on the Earth. In this paper, the dynamic evolution of fragments formed as result of the disintegration of near-Earth asteroids (NEA) is considered. To simulate the decay of an asteroid a model of an asteroid detonation using a nuclear charge has been applied.

In the previous paper [6] we have considered a variant of an asteroid destruction a few years before its predicted fall and showed that the project is feasible and reduces the danger of radioactive contamination to an acceptable level: the preventive destruction of an object long before the subsequent collision leads to the fact that all or almost all fragments leave the orbit of the collision. In [6] we assumed that a nuclear device is delivered to the asteroid by a spacecraft that catches it up in the heliocentric orbit. Generally it requires large geocentric velocities. For example, the speed of Apophis during the close approach in 2029 to distance of about 38 thousand km will reach 7 km/s.

In this paper, we consider another method of an asteroid explosion requiring a small geocentric velocity of the spacecraft. In this case an asteroid in heliocentric motion overtakes the spacecraft and not vice versa. Thus the explosion decelerates the fragments in their heliocentric motion. From the point of view of physics and mathematics, the change in the formulation of the problem is small. Only the velocity distribution of the fragments is transformed (both in magnitude and direction). Therefore,
we give below only a scheme for statement and solving the problem referring the reader to the paper [6] for details.

For short, we call "the variant I" the case with the projectile overtaking the asteroid, and "the variant II" the opposite one.

2. Simulation of the explosion

At the time of the explosion the coordinates of the asteroid fragments were assumed to be equal to the coordinates of the parent body. The initial spatial distribution of particles’ velocities has been constructed using the "Numerical model of disintegration" [9]. Let us give the main formulas.

The velocity components are determined by the formula:

\[
\begin{align*}
\dot{x}_{10} &= v_1 + v_t \cos \tau, \\
\dot{x}_{20} &= v_2 + v_t \sin \tau \cos \phi, \\
\dot{x}_{30} &= v_3 + v_t \sin \tau \sin \phi,
\end{align*}
\]

where \(v_1, v_2, v_3\) are the components of the asteroid velocity in the heliocentric coordinate frame, \(v_t\) is magnitude of the velocity vector of the fragments relative to the parent body. The parameters \(\tau\) and \(\phi\) define the direction of the velocity vector of a fragment relative to the parent body and they are treated as random variables with given density distribution functions \([6, 9]\):

\[
f_1(\phi) = \frac{1}{2\pi}, \quad f_2(\tau) = \sin \tau,
\]

with \(\phi \in [0, 2\pi]\) relative to the vector \(\mathbf{v} = (v_1, v_2, v_3)\), \(\tau \in [0, \pi/2]\) and \(\tau \in [\pi/2, \pi]\) relative to \(\mathbf{v}\) in the versions of the explosion I and II, respectively.

The velocity of fragments relative to the parent body \(v\) (m/s) is given by the following distribution density function \([6]\):

\[
f_1(v) = \frac{3}{2\sigma R^3} A^{1/\alpha} v^{-(3+\sigma)/\alpha} \left(1 - \frac{1}{2R} A^{1/\alpha} v^{-1/\alpha} \right), \quad \frac{A}{(2R)^\alpha} \leq v \leq \infty
\]

where \(A = 0.980 \cdot 10^{-6}\), \(\sigma = 1.74\), and \(R\) is radius of the asteroid (m).

We introduced a new dimensionless random variable to simplify the distribution function \(\xi\):

\[
\xi = \frac{1}{2R} A^{1/\alpha} v^{-1/\alpha}, \quad v = \frac{A}{(2R)^\alpha} \xi^{-\sigma},
\]

In accordance with \([7]\), the distribution density function for \(\xi\) has the form:

\[
f_\xi(\xi) = 12\xi^2 (1 - \xi), \quad 0 \leq \xi \leq 1,
\]

then the distribution function can be defined by the formula:

\[
F(\xi) = \xi^3 (4 - 3\xi), \quad 0 \leq \xi \leq 1
\]

According to the method of inverse functions \([10, 11]\) we may use the uniformly distributed in \([0, 1]\) random variable \(\xi\) connected with \(\gamma\) by the equation:

\[
\xi^3 (4 - 3\xi) - \gamma = 0,
\]

where \(\gamma\) is a random variable from 0 to 1.
In the "Numerical model of disintegration" $\xi$ is calculated by an iterative method. This model is described in more detail in [6, 9].

3. Explosion consequences

To simulate the explosion, a model object was selected from the confidence region of asteroid 99942 Apophis obtained on base of observations up to 2009 [12]. This object passes on April 13, 2029 at a distance of 36838 km from the geocenter, and on April 13, 2036 it moves at 1270 km, i.e. it actually collides. The diameter of the asteroid was taken equal to 200 m, and its density to $\rho = 2500$ kg/m$^3$ (corresponding to material such as monolithic granite). Due to the explosion the asteroid is completely destroyed into fragments up to 10 m in size in accordance with the given destruction model (real asteroids have an irregular shape and can be either more or less solid, however, since the task of this study is to give a qualitative picture, some idealization of the model problem is permissible [6]).

The number of generated fragments of the breakup was taken equal to 100000 for greater statistical validity in the calculations. In the study of the orbital evolution of the particle stream resulting from the explosion a highly accurate software complex "IDA" was used, which was designed to examine the dynamics of asteroids [13]. The asteroid fragments’ motion on the interval from 2029 to 2040 was considered for each variant of the explosion.

The evolution of the particles was simulated by numerical integration of the motion equations by Gauss-Everhart’s method of the 19th order. We take into account the following perturbing factors: the influence of 8 planets, Pluto, the Moon, Ceres, Pallas, Vesta and the Earth oblateness. In the process of research close encounters and collisions with the Earth were revealed.

The results of the investigation of the orbital evolution of the asteroid fragments are shown in table 1, where the statistics of close encounters and collisions of particles with the Earth are presented. The table presents for each year the number of particles passing through the gravitational sphere of the Earth $N_{tg}$ (radius of the gravity sphere is $\approx 255812$ km), the number of particles colliding with the Earth $N_{coll}$, and the minimum distance from the center of the Earth $d_{min}$ determined over all fragments. In this case the explosion was carried out at 4 hours and 38 minutes after the close approach on April 13, 2029 (JD = 2462240.6), let us denote this time as $t_1$. The distance to the Earth is about 114 thousand km, i.e. the destruction of the asteroid occurs within the sphere of gravity of the Earth.

| Year | $N_{tg}$ | $N_{coll}$ | $d_{min}$ (km) | $N_{tg}$ | $N_{coll}$ | $d_{min}$ (km) |
|------|----------|------------|----------------|----------|------------|----------------|
| 2029 | 49       | 0          | 47956          | 82       | 8          | 1541           |
| 2030 | 7        | 0          | 81328          | 33       | 3          | 6160           |
| 2031 | 8        | 0          | 43934          | 30       | 0          | 8145           |
| 2032 | 2        | 1          | 4433           | 25       | 2          | 6163           |
| 2033 | 1        | 0          | 99914          | 22       | 2          | 6391           |
| 2034 | 18       | 0          | 12893          | 20       | 0          | 9118           |
| 2035 | 94       | 2          | 1905           | 21       | 0          | 9266           |
| 2036 | 143      | 4          | 777            | 155      | 8          | 3571           |
| 2037 | 1        | 0          | 172932         | 167      | 5          | 2685           |
| 2038 | 4        | 0          | 61313          | 75       | 0          | 8935           |
| 2039 | –        | –          | –              | 32       | 1          | 6141           |

As for the first variant the results show that in total in the different years (2032, 2035, 2036) only 7 fragments fall. The greatest number of close approaches and collisions occurs in 2036 that corresponds to the fall of the initial object. This variant can be considered relatively safe and quite acceptable. In the case when the asteroid overtakes the spacecraft with nuclear charge, the situation is much worse. As a result of the second variant of the explosion, a significant part of the debris rushes
back to Earth, 8 pieces fall to Earth immediately, carrying a significant radioactivity. The falls continue in subsequent years. It should be noted that even when not a single particle (2031, 2034, 2035 and 2038) falls, some of the debris passes very close to the Earth (at a distance of less than 10000 km). Thus the second version of the explosion should be recognized as unacceptable.

Next, an experiment was conducted. We tried to find out whether it is possible to avoid the collisions in 2029 if the explosion was displaced at a later time and correspondingly to a larger distance from the Earth. For this purpose, the moment 9 hours and 26 minutes after the approach (\(t_2 = 2462240.8\) JD) was considered (the asteroid was located at a distance of 218 thousand km from the geocenter). The results of this simulation are given in table 2, where the designations are similar to those in table 1. As we can see from table 2 the change in the explosion moment had a small effect on the first option. In the second case the number of collisions decreased slightly but in principle the picture did not change.

Table 2. Estimates of the consequences of the explosion (point in time \(t_2\)).

| Direction of explosion | I          |          | II          |          |
|------------------------|------------|----------|------------|----------|
| Year       | \(N_{og}\) | \(N_{coll}\) | \(d_{min}\) (km) | \(N_{og}\) | \(N_{coll}\) | \(d_{min}\) (km) |
| 2029       | 41         | 0         | 85331      | 67       | 4         | 301         |
| 2030       | 0          | 0         | –          | 19       | 1         | 3400        |
| 2031       | 0          | 0         | –          | 15       | 0         | 32336       |
| 2032       | 1          | 0         | 170854     | 9        | 0         | 9721        |
| 2033       | 6          | 0         | 60674      | 13       | 2         | 1970        |
| 2034       | 20         | 1         | 5491       | 11       | 0         | 13413       |
| 2035       | 90         | 4         | 1309       | 7        | 0         | 28493       |
| 2036       | 121        | 7         | 1130       | 189      | 7         | 227         |
| 2037       | 3          | 0         | 95365      | 142      | 3         | 2805        |
| 2038       | 4          | 0         | 17591      | 48       | 1         | 2556        |
| 2039       | –          | –         | –          | 23       | 0         | 8703        |

Let us consider more thoroughly how the fragments are distributed after the explosion. As an example figure 1 (a)-(d) shows the position of the particles in one year after the explosion in all considered cases. Figures 1 (a) and 1 (c) correspond to the first variant of the explosion, and figures 1 (b) and 1 (d) relate to the second one. The explosion in figures 1 (a) and 1 (b) was carried out at time \(t_1\) and the explosion in figures 1 (c) and 1 (d) was executed at time \(t_2\). The line shows the orbit of the parent body from the moment of destruction to \(t_1\) and \(t_2\), respectively. On all graphs the symbol "+" indicates the position of the exploded object, the Earth is marked by its astronomical symbol.

As we can see from figures 1 (a) and 1 (c), in the case I the maximum concentration of particles corresponds to the vicinity of the initial object, the others lie behind and form a "trail". The other picture is typical for the case II (figures 1 b and 1 g). In a year the fragments are distributed along the whole of the orbit which leads to possible encounters and collisions with the Earth throughout all the year. It should be noted that the variant I of the explosion leads to an increase in the velocity and the semimajor axis of most fragments. The second variant has the opposite effect that in particular leads to close approaches with the Earth from the Sun side. Such close encounters and collisions can be unnoticed in advance.

It can be seen from the figure 1 that a year later the asteroid particle torus closes up only in the second version of the explosion. In order to detect the closing time for the first variant figure 2 presents similar data two years after the explosion. Most of the particles are distributed along an orbit with a semimajor axis greater than that of the parent body. This figure corresponds to the asteroid destruction at the time \(t_1\), the graphs for the time \(t_2\) are not given since the particle distribution has no fundamental differences in considered cases.
In addition, we made an assessment of the radioactivity of asteroid fragments that fell to Earth. The overall activity $Q$ of matter an hour after a megaton nuclear explosion is extremely high (300 GCi) but falls rapidly with time. It was shown in [14] that the rate of decay of a large number of isotopes varies according to a complex law. But it may be approximated by power law on time from some minutes to some years

$$Q = q t^{-1.2},$$

where $q=5.5$ if activity is determined in MCi and time $t$ is measured in years.

In the worst case of the variant I the radioactivity of the first felt fragments is 1.0 MCi and in the second variant lies from 12 up to 111 MCi, which also indicates the inapplicability of the second way.

![Figure 1. Projections of the position of the particles («●»), the Earth («⊙»), and the exploded asteroid («+») on the equatorial plane one year after the explosion](image_url)
4. Conclusion

The paper presents the results of numerical modeling of an asteroid explosion immediately after the close approach preceding the collision. Two variants of the explosion have been considered: in the first case a space vehicle with a charge overtakes an asteroid; in the second case the situation is opposite. The evolution of the resulting debris showed that the second option requires significantly lower launch rates. On the other hand it significantly loses to the first one since more fragments fall to the Earth. Although with a more careful approach (non-isotropic explosion) likely this unfavorable factor can be reduced. We shall consider it in a future work.

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