THE CONDITIONS FOR APOPHIS 99942 APPROACHING EARTH IN 2029

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ABSTRACT. The discovery of Apophis 99942 asteroid in 2004 raised a number of questions in the sphere of the asteroid threatening. On April 13, 2029, the asteroid is to pass at a close distance from Earth. The study of the path of that asteroid both before and after such close approaching showed that the repeated passing by Earth and even its collision with Earth is possible in April, 2036.

In the present work, the area of the resonant return of asteroid Apophis, the Moon influence to its shape and position are considered.

Asteroid Apophis 99942 was discovered on June 19, 2004, at Kitt Peak National Observatory. The computed parameters of the asteroid orbit allowed of assigning it to the class of Near-Earth asteroids (NEA). Its orbital plane is inclined 3^0 to the ecliptic plane, and the semi-major axis is 0,9233 AU [1]. Therefore, the asteroid orbit is close to the Earth's orbit, but its passing is far from the higher-order resonance [2]. The first evaluations of the orbital elements showed that the collision of the asteroid with Earth is probable on April 13, 2029. On having additional radar observations carried out and more accurate definition of the orbital elements made, the probability of the impact was ruled out. The asteroid is to approach Earth up to 37600 km; then, it is to pass the Moon at a distance of 97000 km and move away along the orbit disturbed by Earth [3, 4, 5]. However, due to the inaccuracy of the initial data, there is a probability of collision of that object to the Planet in 2036 and the future years. Different researchers estimate the mathematical probability of the collision as $2{,}2 \times 10^{-5}$ [5] and $2{,}5 \times 10^{-5}$ [6]. Besides, there is a theoretical possibility of such collision later in the future; but it is much lower than the probability in 2036.

The study of the evolution of the orbit of Apophis asteroid has been conducted within the bounds of the problem of 14 bodies in the rectangular heliocentric coordinate system relative to the equator and the equinox 2000.0. In the model, the disturbances of the major planets of the solar system, Pluto, the Moon, the largest three asteroids (Ceres, Pallas and Vesta), the light pressure and the Earth oblateness were taken into account. The positions of the major planets, Pluto and the Moon were adopted from the numerical theory DE405/LE405 [7, 8]. The coordinates of Ceres, Pallas and Vesta were determined by the numerical integration of the equations of their movement, the initial conditions for which were taken from the E. Bowell catalogue [9]. When taking into account the influence of the light pressure, the albedo of the asteroid was considered to be equal to 0.3, and the diameter - to 260 m. At the time of the present article has been written, the error of the above mentioned parameters was equal to ±0.08 and ±60 m, respectively.

The combined differential equations of the system bodies' movement were solved by the numerical integration method by Everhart of the 15^{th} order [10] with the possibility to control the accuracy. In the present study, the accuracy of 0.01 mm was maintained at each integration step; and during the computations, the integration step has been changed from 4 days at the moment of the asteroid's maximum moving away from Earth to 6 minutes at the moments of the minimum approaching at that.

Using the derived system, we studied the evolution of the asteroid orbit during the period of 2004-2036. The following state vector was taken as the nominal initial condition for the asteroid at the moment JD = 2453360.5:

$$\begin{cases} X = 0.08942742963075248 \\ Y = 0.89794430458694535 \\ Z = 0.33638610886252548 \\ Vx = -0.0164623245524509 \\ Vy = 0.00458223264966611 \\ Vz = 0.00128067462049327 \end{cases}$$

the error in component coordinates was 5 km, and in component velocity was 0,0022 m/s. [11]

In the result of the integration of the initial conditions, without taking into account the error, we received the nominal orbit of the asteroid. However, such an orbit do not enable to make any conclusions about the probable area of the asteroid passing as, during the integration, the error in definition of the path is growing. To estimate the error value, we applied the following method.

We considered the distribution of the probability density of the error of each coordinate and the Gaussian component of the velocity vector. Let ξ be one of the parameters (coordinate or the velocity component); then, if $\Delta\xi$ is the error in definition of that parameter (coordinate or the velocity component) ($\xi \pm \Delta\xi$), the standard deviation is $\sigma(\xi) = \frac{\Delta\xi}{\sqrt{3}}$.

By means of such a simple algorithm, we received the group of 250 thousands possible initial conditions. By integrating that bunch in the interval of 2004-2036, we obtained N (250 thousands) of probable orbits of the asteroid, enveloping the nominal orbit. Such approach enabled to study the evolution of the orbit of Apophis asteroid, taking into account the errors in the initial value of the state vector.

It took 6-7 seconds to integrate a separate initial condition. However, by the specificity of the integration algorithm, we could parallelize the computations that allowed of cutting the time of computations by 2-3 times. Hence, it took 5-6 days to carry out all computations with the 4-kernels processor Core Quad of 3 KHz and 8 GB of the on-line storage.

In accordance with the results of the numerical integration, the asteroid is to closely approach to Earth two times: on April 13, 2029, and on April 13, 2036. The dependency of the distance of the asteroid to Earth from time is still almost constant for all 250 thousands of the initial conditions up to the moment of the first approaching.

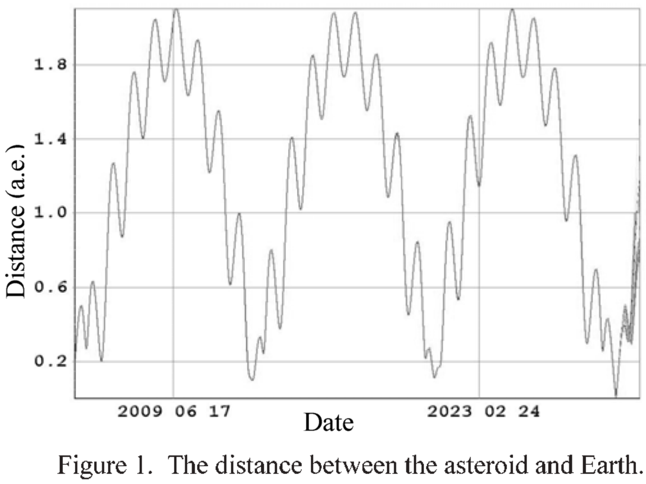

Figure 1. The distance between the asteroid and Earth.

After the first approaching, the error of definition of the position of the studied object is growing that enables to more accurately determine its position. It is possible to say that April 13, 2029 is the key moment which determines the conditions for Apophis approaching to Earth in 2036.

From the whole group of the possible initial conditions, only 40382 orbits are approaching to Earth in 2036 closer than 40000 km. Among them, 28 orbits intersect the Earth's surface. The estimation of probability of such events as approaching and collision of the asteroid with Earth in 2036 give the following values: 0,16% – the probability of the asteroid pass around Earth in 2036 closer than 40000 km and 0,00011% – the probability of the asteroid impact with Earth in 2036.

Among the whole bunch of the initial conditions, the most interesting for the studying are those that cause the collision of the asteroid with Earth in 2036.

As the conditions of the approaching on April 13, 2029 are to determine the further evolution of the asteroid orbit, we tried to define the area of the near-Earth space-time where the asteroid, on having entering that area, is to approach the trajectory to impact with Earth in 2036. Due to the narrow dimensions of that area, it is called the "keyhole" [12].

It is obvious that the precise position and dimensions of the "keyhole" are of great interest. To determine those in 6-dimensional phase space of coordinates-velocities near 28 state vectors that lead to the collision of the asteroid with Earth in 2036, we generated additional 60 thousands of possible trajectories. Those were obtained by variation of each coordinate and velocity component of the asteroid as of April 13, 2029. The integrating of the group of trajectories, received by that way, up to April, 2036, showed that 6.5 thousands of trajectories intersect the Earth's surface at that moment. Thus, the position of those trajectories as of April, 2029, is to give a view of the "keyhole".

The possible positions of the asteroid during its approaching Earth in 2036 are shown in Fig. 2. 6.5 thousands of positions that lead to the collision are marked as circles; the orbits that approach to the center of Earth at the minimal distance of 7000-10000 km are marked as crosses.

The same possible positions of the asteroid at the maximum approaching on April 13, 2029 are presented in Fig. 3. At that moment, the positions on the trajectories that lead to the collision in the future (marked as circles) and the positions on the trajectories that do not cause the catastrophe (marked as crosses) and that to be away from the center of Earth at the distance of 7000-10000 km in 2036 occupy the same area in space. We did not succeed in determination of the shape of the "keyhole" and in separation of two types of the trajectories.

The numerical modeling shows that on having approached Earth, Apophis is to fly by the Moon 24 hours later. The distance between the celestial bodies will diminish to 95876 km. The change in distance between them from April 13 to April 16, 2029, is shown in Fig. 4.

When the asteroid passes the point of the minimal approaching to the Moon, the probable orbits are divided in two separate groups. Apparently, the Moon's gravitational field disturbs the asteroid's movement by the diluting of the "keyhole" near Earth.

To check such an assumption, we carried out the modeling of the asteroid's movement with the same group of the possible trajectories, but not taking into account the Moon's gravity. Some numerical criterion of the display of the lunar disturbances was demanded. We chose the average square of distances between the momentary positions of the asteroid that lead to the collision with Earth in 2036 (x_i, y_i, z_i), and that do not cause such an impact (ξ_j, η_j, ζ_j):

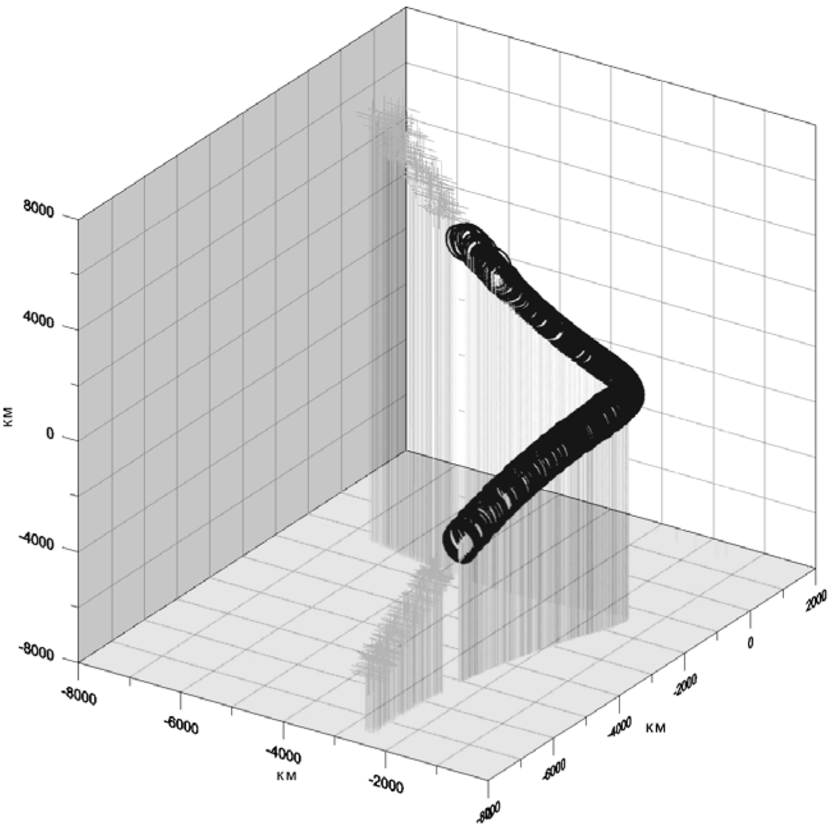

Figure 2. The asteroid's position relative to Earth as of April 13, 2036.

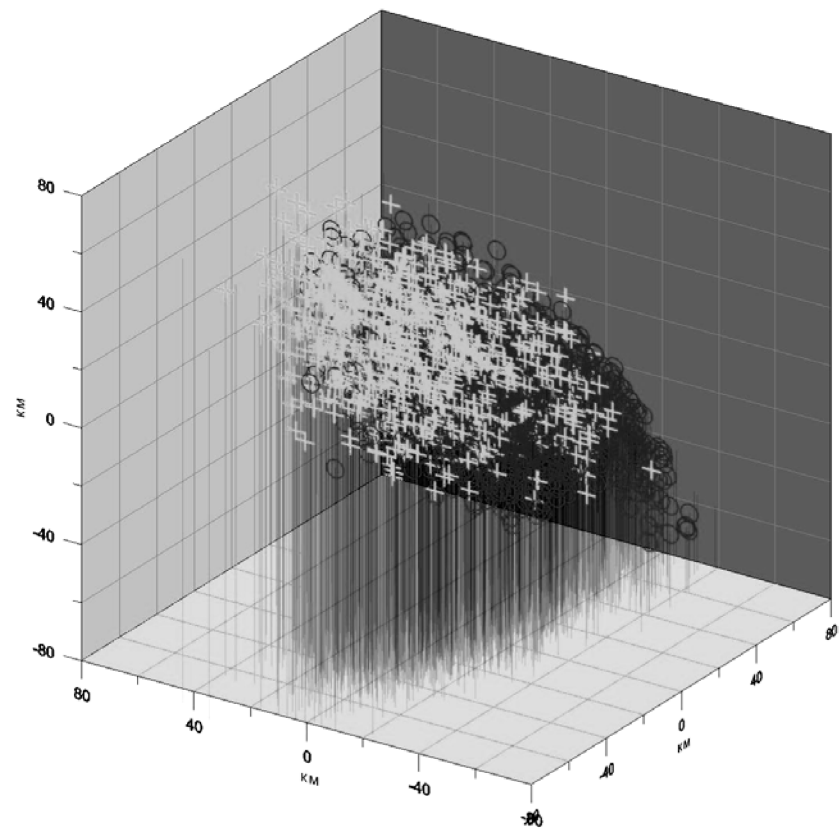

Figure 3. The same possible positions of the asteroid at the maximum approaching on April 13, 2029

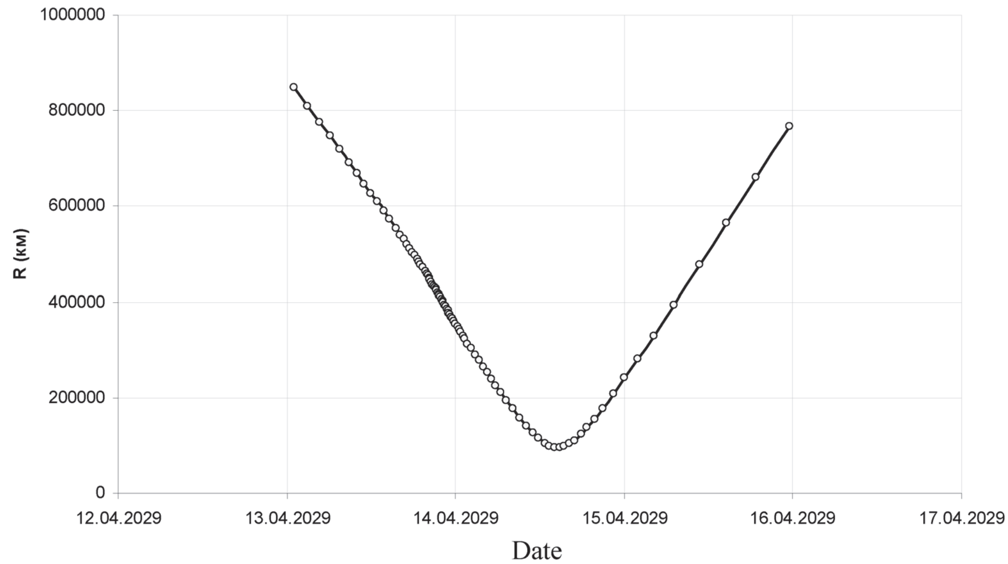

Figure 4. The distance between the asteroid and the Moon.

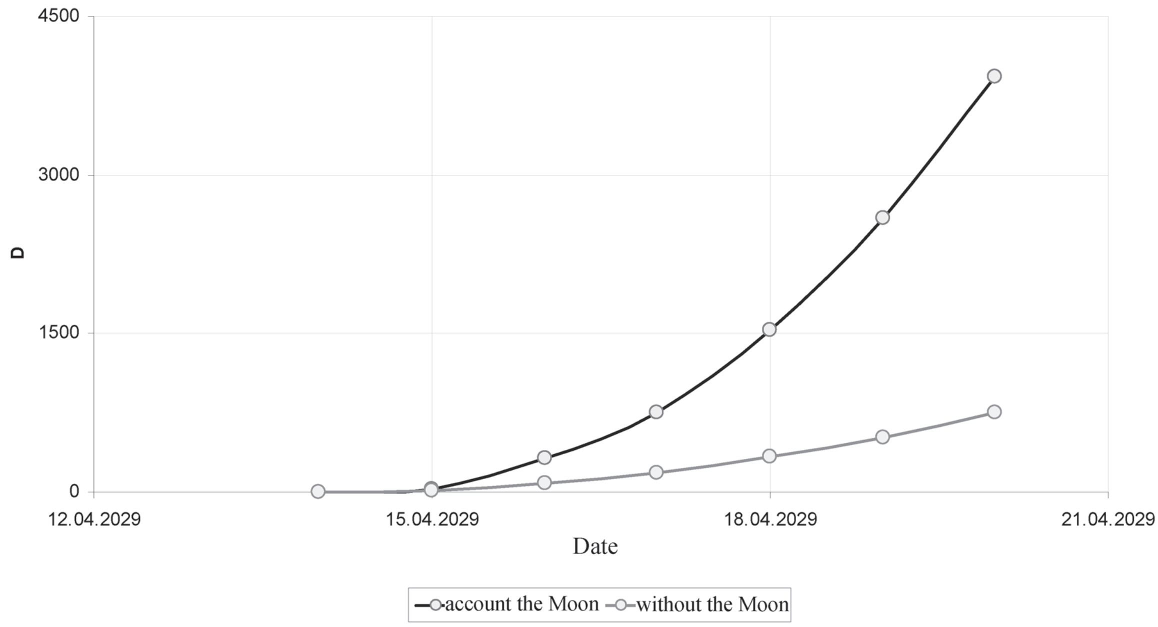

Figure 5. Parameter D

$$D=\sum_{i=1}^{n}\sum_{j=1}^{m}\left((x_i-\xi_j)^2+(y_i-\eta_j)^2+(z_i-\zeta_j)^2\right).$$

The value of D parameter is considered to be 1 at the moment of the maximum approaching to Earth. The variation in value D, taking into account the lunar disturbances and without doing that, is shown in Fig. 5. The lunar disturbances monotonously increase value D. That confirms the assumption that the Moon has a "diluting" influence on the "keyhole" near Earth.

Thus, after the close approaching to Earth on April 13, 2029, asteroid Apophis is to approach the Moon on April 14 at 14:47 UT at the distance of 95876 км. That approaching is to influence also on the growth of the uncertainty of the asteroid's movement in future. It is possible that the position of the "keyhole" should be found in the group of its possible trajectories not near Earth, but near the Moon.

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