Study of the orbital dynamics of asteroid 2023 BU, which made a record approach to the Earth

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As part of the Pulkovo program for the study of near-Earth objects, more than 1500 observations of asteroid 2023 BU, which was discovered at the very beginning of 2023 just a few days before its extremely close approach to the Earth at a distance of about $3.5 \cdot 10^6$ m from its surface, were made at the MTM-500M telescope. It was one of the closest encounters of an asteroid with the Earth ever recorded, which caught the attention of astronomers around the world. Based on the observations of this asteroid, its orbit was refined and the orbital evolution was studied. In addition, estimates of the influence of solar radiation pressure and the Yarkovsky effect were made, which is relevant due to the problem of asteroid and comet hazard.

Keywords: Near-Earth asteroids, astrometry, solar radiation pressure, the Yarkovsky effect.

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Asteroid 2023 BU with a diameter of about 6 m was discovered on January 21, 2023 by the Russian astronomer G.V. Borisov in the urban-type settlement Nauchny (Crimea). It is noteworthy that the image of this object was first obtained a few days before its close approach to the Earth on January 26, 2023. Due to its small size, this asteroid is not potentially hazardous, but it passed at a record close distance from the center of the Earth, about $9.9 \cdot 10^6$ m [1], and since the radius of the Earth is approximately $6.4 \cdot 10^6$ m, this means that it passed only $3.5 \cdot 10^6$ m from the surface of our planet.

Observations of asteroid 2023 BU were carried out at the Mountain Astronomical Station of the Central (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences in the period from January 25 to January 28, 2023 using the MTM-500M telescope [2]. More than 1,500 observations were received and sent to the Minor Planet Center (MPC). Our observations account for 83% of all global observations of this asteroid. Considering our observations in the MPC, the orbit of the asteroid was improved [3]. The results of the refinement of the elements of are presented in Table 1.

Table 1. Orbital elements of asteroid 2023 BU at epoch JD2460000.5

Mean anomaly M	28.72773°
The argument of perihelion ω	355.74682°
Longitude of the ascending node Ω	125.48523°
Inclination i	3.74897°
Eccentricity e	0.1110826
Semi-major axis a	1.1070054 AU

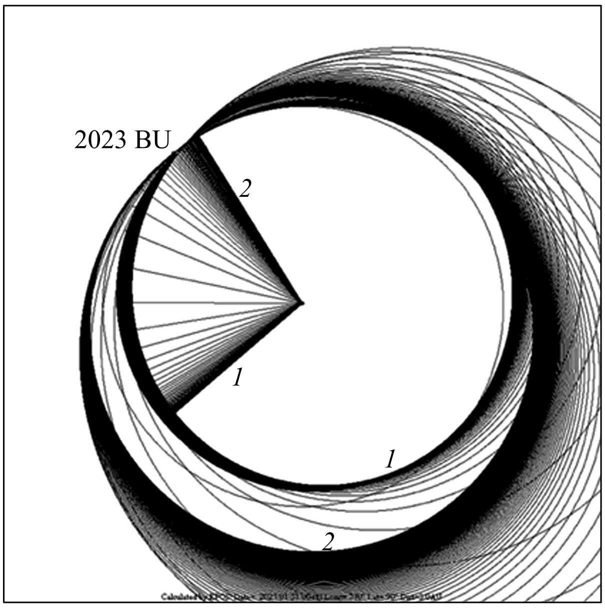

Figure 1. Change in the orbit of asteroid 2023 BU.

This approach to the Earth was one of the closest ever recorded and entailed a change in the asteroid's orbit, which is illustrated in Fig. 1. It shows the change in the orbit along with the apse line in the time interval January 25–31, 2023 in increments of $6 \cdot 10^2$ s. The numbers *1* and *2* correspond to the initial and final time. The images of the asteroid and the Earth practically merge. In a short period of time, the orbit quickly „swells" and rapidly „collapses", but already taking on new size and shape. Fig. 2 shows a graph of changes in the semi-major axis of the asteroid's orbit for 1700–2100. Two more smaller orbital changes are noticeable (1858–1862, several moderate approaches) and

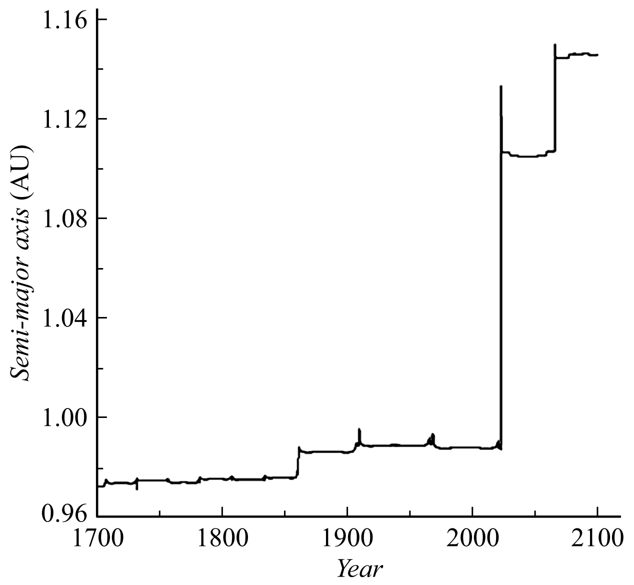

Figure 2. Change in semi-major axis of the orbit (AU) of asteroid 2023 BU in 1700–2100

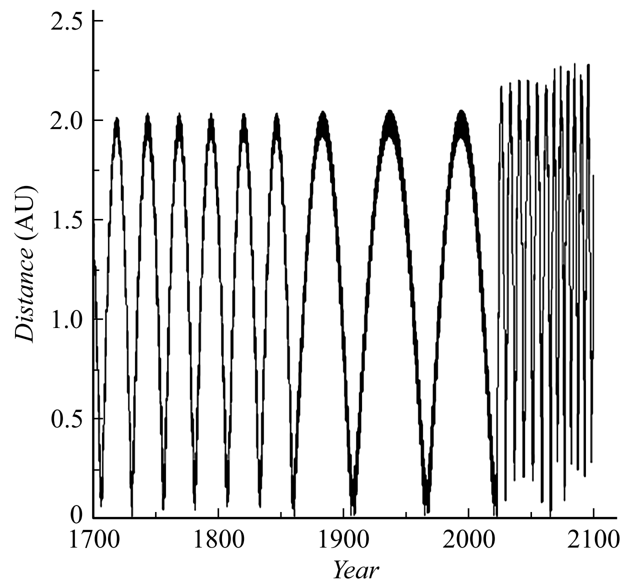

Figure 3. Change in distance (AU) of asteroid 2023 BU from the Earth in 1700–2100

in 2066 (distance 0.0035 AU). Fig. 3 shows the change in the asteroid's distance from the Earth over the same period of time. It can be seen that the quite regular movement of the asteroid acquires a more chaotic character due to repeated approaches to the Earth.

In 2029, the next approach of the asteroid is expected to be at a distance of the order of $1.3 \cdot 10^{10}$ m from the Earth, and in 2066 — at a distance of about $5.3 \cdot 10^{8}$ m, which is the closest approach of all the coming approaches in this century. In this regard, the calculations of deviations under the influence of radiation pressure were carried out on two time intervals, 6 and 43 years, which corresponds to close

Table 2. Orbital shift of asteroid 2023 BU under the influence of radiation pressure after 6 and 43 years, depending on the density of the asteroid

Year	1380 kg/m^3	2710 kg/m^3	5320 kg/m^3
2029	$1.9 \cdot 10^3$ m	$0.9 \cdot 10^3$ m	$0.5 \cdot 10^3$ m
2066	$2.6 \cdot 10^4$ m	$1.3 \cdot 10^4$ m	$6.7 \cdot 10^3$ m

Table 3. Magnitude of the Yarkovsky effect $\Delta a \cdot 10^{-10}$ AU per revolution around the Sun as a function of the inclination angle of the rotation axis and the rotation period P_{rot}

P_{rot}, s	0°	45°	90°	135°
$3.6 \cdot 10^3$	1.3772	0.9666	−0.0144	−0.9810
$1.8 \cdot 10^4$	0.9369	0.6553	−0.0144	−0.6697
$3.6 \cdot 10^4$	0.7371	0.5140	−0.0144	−0.5285
$5.4 \cdot 10^4$	0.6315	0.4393	−0.0144	−0.4537

approaches in 2029 and 2066. Initial data for calculations are presented on the MPC website [3]. Inasmuch as the density of the asteroid required to estimate its mass is unknown, calculations were performed for three values of the average density of the main spectral classes of asteroids (C, S, M) [4]. The asteroid's albedo δ, equal to 0.06, was calculated using the formula $\lg D = 3.122 - 0.5 lg\delta$-$0.2H_v$ [5], where D — is the diameter of the asteroid, H_v — is the absolute magnitude of the asteroid. The method of calculation is described in detail in the paper [6]. The calculation results are given in Table 2. Significant deviations of the asteroid are due to its small size. It is noticeable that they rapidly decrease with increasing density. Asteroid 2023 BU belongs to the Apollo family, which predominantly represents S-class objects, which means that the deviations are likely to be close to those calculated for a density of 2710 kg/m^3.

Estimates of the Yarkovsky effect were also made, which is the acceleration or deceleration of the orbital motion of a body due to the appearance of a weak reactive impulse as a result of asymmetric re-emission of thermal energy by the surface of the body.

Due to the fact that the inclination angle of the rotation axis and the rotation period P_{rot} of the asteroid are unknown, calculations of the Yarkovsky effect were performed for a number of model values of these parameters (Table 3). The density of the asteroid required for the calculations was assumed to be 3137 kg/m^3, which corresponds to the arithmetic mean of the density of the main spectral classes of asteroids. The emission, thermal conductivity and heat capacity coefficients are taken as average: $\varepsilon = 0.9$, $K = 10^{-2}$ W/(m · K), $C = 500$ J/(kg·K). The thermodynamic model of the Yarkovsky effect was taken from the papers [7,8]. The method for calculating the magnitude of the Yarkovsky effect is taken from the paper [9]. The results of calculations are presented in Table 3. Positive values correspond to an increase in the semi-major axis, i.e. deceleration of movement, negative values — to a decrease, i.e. acceleration. Obviously, the magnitude of the change in the semi-major axis decreases with the increase in the rotation period of the asteroid.

In conclusion, it should be noted that the estimates of orbital evolution obtained, as well as the results of deviations due to the influence of non-gravitational effects, especially radiation pressure, are quite significant. In this regard, they should be considered in further calculations of the trajectory of movement. It should be emphasized that the study of asteroids is important in the scope of the problem of asteroid-comet hazard, and although asteroid 2023 is not hazardous for the Earth, it is undoubtedly of interest for its early detection and such a close approach to the Earth.

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Conflict of interest

The authors declare that they have no conflict of interest.

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