ASTROMETRIC AND PHOTOMETRIC STUDIES OF POTENTIALLY HAZARDOUS ASTEROID (138971) 2001 CB21

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In 2022 astrometric and photometric observation series of potentially hazardous asteroid RAS received astrometric and photometric series of observations of a potentially dangerous asteroid (138971) 2001 CB21 were obtained with the MAO RAS telescope during its close approach to Earth. Based on the obtained data and data from the MPC website, the asteroid's orbit was improved, circumstances of close approaches to Earth and Venus were investigated, and an assessment of the influence of non-gravitational effects on its motion was made. Based on photometric observations of the asteroid, a light curve was constructed and the period of its axial rotation was confirmed: $P = 3.305 \pm 0.002$ h.

Keywords: potentially hazardous asteroid, astrometry, photometry

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INTRODUCTION

Asteroid (138971) 2001 CB21 was discovered on February 2, 2001, by the Lincoln Near-Earth Asteroid Research (LINEAR) in Socorro (New Mexico, USA). It belongs to the Apollo group and is classified by the Minor Planet Center (MPC) as potentially hazardous to Earth (minimum orbit intersection distance MOID = 0.02377 AU) (MPC web-page). The asteroid's diameter ranges from 0.340 km (Usui et al., 2011) to 0.578 km (Mueller et al., 2011). The axial rotation period was determined as 3.3020 ± 0.0008 h. (Galád et al., 2005).

OBSERVATIONS

Asteroid (138971) 2001 CB21 was observed with the ZA-320M telescope (Devyatkin et al., 2004) at Pulkovo Observatory for five nights from February 26 to March 4, 2022. The circumstances of the observations are presented in Table 1. The values of the average brightness, phase angle, and coordinates of its bisector were calculated using the EPOS software package (Lvov, Tsekmeister, 2012) based on the asteroid's orbital elements obtained from the Minor Planet Center website (MPC web-page 2).

The ZA-320M telescope is located on the territory of the Pulkovo Observatory (Saint Petersburg). It has a Cassegrain optical design with a primary mirror diameter of 320 mm, focal length of 3200 mm, and a scale of 64.5 ″/mm. The telescope is equipped with a ZWO ASI-1600 (mono) CCD camera, which provides a field of view of 18′.8 × 14′.2. During observations, 4 × 4 pixel binning is used, giving an angular pixel size of 0″.97 × 0″.97. Observations were conducted without filters – in the integrated band of the instrument.

Table 1. Circumstances of observations of asteroid (138971) 2001 CB2

Date (evening)	Interval (UTC)	Exposure, s	Number of frames	*m*	PA, deg	PABL, deg	PABB, deg
2022-02-26	21:40 – 01:42	30	150	14.3	61.9–62.7	181.2–181.7	24.8–25.1
2022-02-27	20:38 – 02:45	20–30	567	14.2	67.0–68.5	184.2–185.1	26.4–26.8
2022-02-28	22:35 – 03:01	20	258	14.2	74.2–75.6	188.5–189.3	28.4–28.7
2022-03-01	22:37 – 03:44	17–20	856	14.3	82.4–84.4	193.5–194.7	30.4–30.8
2022-03-04	03:17 – 03:27	20–40	19	15.7	116.6–116.7	216.7–216.8	34.7

Note: Listed are: evening dates, time intervals, exposure durations, number of frames, average stellar magnitudes (*m*), phase angles (PA), ecliptic longitudes (PABL) and latitudes (PABB) of the phase angle bisector.

ASTROMETRY AND ORBIT INVESTIGATION OF THE ASTEROID

A total of 1419 frames obtained with the ZA-320M telescope were used for astrometric and photometric processing.

During the processing of observations, the software packages APEX-II (Devyatkin et al., 2010) and EPOS (Lvov, Tsekmeister, 2012), developed at the Pulkovo Observatory, were used.

Astrometric reduction was performed using the eight-constant method. The Gaia DR2 catalog (Gaia Archive web-page) was used as a reference.

The current elements of the asteroid's osculating orbit are based on multiple positional observations over the past period of time. When a sufficient volume of new observations is obtained, it is possible to refine these elements, or, as it is commonly said, to improve the orbit.

The ORBIMPR program, which is part of the EPOS package, allows for the improvement of current orbital elements of celestial bodies using the entire set of available observations based on two modifications of the differential method of orbit correction. The conditional equations contain corrections either to the elements or to the rectangular coordinates, referred to a certain point in time, which are associated with the (O-C) values for right ascension and declination, calculated using the initial orbital elements for each observation. In the first case, the coefficients of the unknowns, with an accuracy up to certain multipliers, are partial derivatives of the rectangular coordinates of the object with respect to the corresponding elements, calculated analytically at a specified point in time. In the second case, the derivatives of rectangular coordinates and velocities with respect to time are estimated numerically. Since the formulas of the method are accurate to first-order terms, the natural condition is the smallness of the mentioned (O-C) values. Large deviations of the observed coordinate values from the improved orbit were filtered out according to the 3 σ criterion.

To improve the orbit, in addition to our observations, results of observations taken from the MPC database were used. When improving the orbit, as a result of 21 iterations from 3446 ground-based observations of the asteroid over the interval 2001.02.02 - 2022.03.04, 2715 were used, of which almost two-thirds were observations from the Main Astronomical Observatory of the Russian Academy of Sciences. The initial value of RMS = $1''.952$, the final value of RMS = $0''.198$. The latter value represents only the final set of observations that was used for improvement. The results for epoch 2459600.5 are contained in Table 2.

Although formal errors are much smaller than the correction values themselves, the result still cannot be considered completely satisfactory: too many observations were discarded during calculations. It should be noted that during close approaches to Earth at 5-7 million km, the two orbits (initial and improved) yield differences in distances from several tens to several hundreds of kilometers. However, the significant effect from this may only manifest in the more distant future.

Currently, the asteroid is a potentially hazardous object simultaneously for both Earth and Venus.

Table 2. Elements of the initial (MPC) and improved orbits of asteroid (138971) 2001 CB21

Orbital elements	Initial	Improved	Corrections	Errors
M, deg	258.08076	258.08074	–0.00002	0.000001
ω, deg	271.81207	271.81200	–0.00007	0.000002
Ω, deg	353.72071	353.72069	–0.00002	0.000002
i, deg	7.89942	7.89939	–0.00003	0.000001
e	0.3333612	0.3333602	–0.0000010	<0.00000001
a, AU	1.03435070	1.03435074	0.00000004	<0.000000001

The calculation of the orbital evolution of asteroid 2001 CB21 was also performed using the EPOS software package. Figure 1 shows a fairly stable pattern of changes in the mutual distances "asteroid – Earth" over a time span of two centuries. Periodic close approaches to Earth are visible. There are twelve such approaches (distances from 0.02 AU to 0.05 AU). If we do not count the date of September 29, 2026, when the mutual distance will be slightly more than the established limit (0.0541 AU), then the next close approach of the asteroid to Earth is expected on March 6, 2043 (0.0322 AU).

No periodicity is observed in approaches to Venus. Over the same time period, close approaches of the asteroid to this planet were noted only twice: in 2004 and 2176.

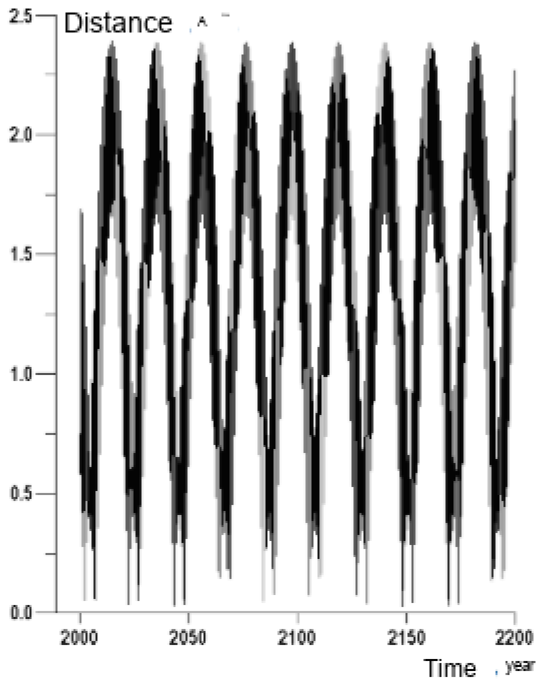

Fig. 1. Result of calculating the changes in distances "asteroid 2001 CB21 – Earth" over time.

ASTEROID PHOTOMETRY AND LIGHT CURVE

Photometric processing of asteroid 2001 CB21 observations obtained with the ZA-320M telescope was also performed using the APEX-II software package (Devyatkin et al., 2010) developed at Pulkovo Observatory, based on the Gaia DR2 catalog (Gaia Archive web-page). The resulting asteroid brightness values were corrected for changes in the asteroid's distances from Earth and Sun, and the phase angle was taken into account assuming that the phase function slope parameter $G = 0.15$. However, differences between mean brightness values obtained on different dates remained afterward. This was corrected by removing a quadratic trend from the data. Segments of the light curve of asteroid 2001 CB21 (138971), obtained from observations with the ZA-320M telescope and subjected to the described reductions, are shown in Fig. 2.

Previously, the rotation period of asteroid 2001 CB21 (138971) was estimated as $P = 3.3020 \pm 0.0008$ h with a full amplitude of brightness variations $\Delta m = 0.12^m \pm 0.02^m$ (Galád et al., 2005). During the asteroid's close approach to Earth in 2022, several observatories performed observations to construct its light curve and determine rotational characteristics. Table 3 shows the results of three such published works. They generally confirm the period value obtained in 2005.

The light curve constructed in this work consists of four segments lasting from 4 to 5.1 h (Fig. 2). Its extreme identical maxima (assuming it has two maxima and two minima) are separated by approximately 76 h, i.e., approximately 23 periods, which allows for reliable determination of its value. This light curve was analyzed using the Scargle method (Scargle, 1982). The obtained values of the period and full amplitude of brightness variations are shown in the last row of Table 3. They correspond to the results of other authors' works listed in Table 3 (with the exception of the paper by Colazo et al. (2022), which provides a rotation period value significantly different from the values in other works, including the present one). Fig. 3 shows the phase light curve, adjusted to the period we determined.

In the work by (Warner, Stephens, 2022), they note the impossibility of precisely aligning different sections of the asteroid 2001 CB21 phase light curve at several tested period values. Based on this, they suggest non-principal axis rotation ("tumbling"), but acknowledge that such a feature in the curve could also arise from shadowing effects at such a significant phase angle (>65°).

As can be seen from Fig. 2, the amplitude of brightness variations determined from our observations increases from February 26 to March 01, 2022, i.e., with an increase in the phase angle from 62° to 84°. Column Δm in Table 3 also shows an increase in amplitude over time, i.e., with phase angle. However, there are no clear indications of possible tumbling rotation in our light curve.

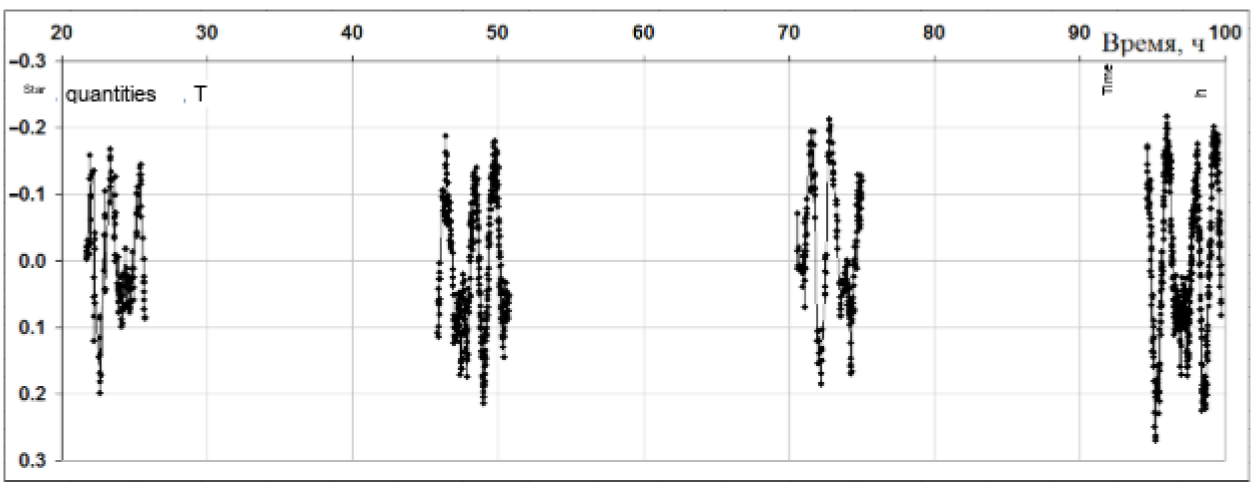

Fig. 2. Fragments of the relative light curve of asteroid 2001 CB21 (138971), obtained with the ZA - 320M telescope on February 26, 27, 28 and March 1, 2022. The horizontal axis shows time in hours, counted from 0 hours UTC on February 26.

Table 3. Rotation period *P* values for asteroid 2001 CB21 (138971) and the full amplitude Δ*m* of its brightness variations, obtained from observations at various observatories during the asteroid's approach to Earth in 2022.

P, h	Δ *m*	Observation dates	References
3.303 ±0.001	0.24 ±0.05	February 8–18	Fornas et al., 2022
3.160 ±0.034	0.24 ±0.05	February 18–25	Colazo et al . , 2022
3.301 ±0.002	0.36 ±0.03	February 27–28	Warner, Stephens, 2022
3.305 ±0.002	0.36 ±0.05	February 26 – March 01	Present work

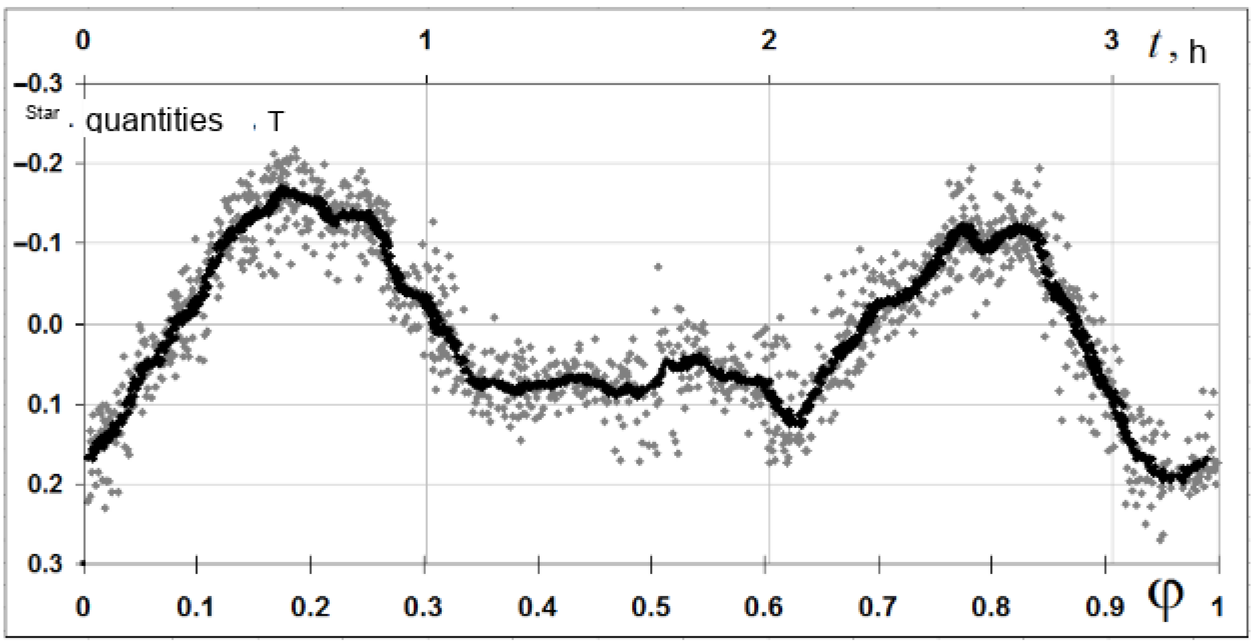

Fig. 3. The phased light curve of asteroid (138971) 2001 CB21, adjusted to the period *P* = 3.305 h, determined in this work. The upper abscissa shows time *t* in hours, the lower one shows the rotation phase φ of the asteroid (the zero point corresponds to the moment 2022.03.02 02:40:48 UTC), the ordinate shows the relative brightness *m*. Gray dots show the observed brightness values, the black curve is the moving average.

ESTIMATION OF NON-GRAVITATIONAL EFFECTS

For asteroid 2001 CB21 estimations of possible values of non-gravitational effects, such as light pressure and the Yarkovsky effect, were made through modeling. Light pressure is the pressure of incident sunlight on the surface of a body, while the Yarkovsky effect is a non-gravitational acceleration or deceleration of a body's motion caused by anisotropic re-radiation of solar radiation from its surface.

The calculations were performed for epoch 2459600.5 (2022.01.21). The initial data are given in Table 2. The asteroid diameter D was taken as the average between the diameter values mentioned in the "Introduction". The mean daily motion is 0.93782550°/day, and the absolute magnitude H is 18.52 (MPC web-page). The geometric albedo of the asteroid δ was obtained using the formula

$\lg D = 3.122 - 0.5\lg\delta - 0.2H$ (Vinogradova et al., 2003) and equals 0.33. As already mentioned, the axial rotation period was determined in this work as 3.305 h.

Since the density or spectral class of the asteroid is unknown, the calculation of light pressure was carried out with three values of average density of the main spectral classes of asteroids (Krasinsky et al., 2002): 1380 kg/m^3 - carbonaceous, 2710 kg/m^3 - siliceous, 5320 kg/m^3 - metallic asteroids. The Yarkovsky effect was calculated with the average density for the main spectral classes equal to 3137 kg/m^3.

The methodology for calculating light pressure is described in (Martyusheva et al., 2015). The total displacement of the asteroid $\Delta d = (\Delta r^2 + \Delta l^2)^{1/2}$, where Δr is the displacement of the asteroid along the heliocentric radius vector, and Δl *is the* longitudinal displacement of the asteroid. Table 4 shows the values of the total displacement of the asteroid Δd under the influence of light pressure over 21 years, which corresponds to the next close approach in 2043.

Table 4. Total displacement Δd of asteroid 2001 CB21 (138971) under the influence of light pressure over 21 years at different density values ρ

ρ, kg/m^3	1380	2710	5320
$\|\Delta d\|$, km	141	72	37

In addition to the specified initial data, the following average values were also adopted for calculating the Yarkovsky effect: emission coefficient – 0.9, thermal conductivity – 10^{-2} W m^{-1} K^{-1}, heat capacity – 500 J kg^{-1} K^{-1}. The inclination angle of the rotation axis γ remains unknown, so calculations were performed for five values: 0°, 45°, 90°, 135°, 180°.

The thermodynamic model of the Yarkovsky effect was taken from (Vokrouhlický, 1999; Vokrouhlický et al., 2000). The calculation methodology was taken from (Panasenko, Chernetenko, 2014). Table 5 presents the values of the change in the semi-major axis of the asteroid's orbit Δ *a* due to the Yarkovsky effect depending on the inclination angle of the rotation axis γ.

Depending on the direction of the asteroid's rotation relative to the direction of orbital motion, the Yarkovsky effect can cause either acceleration of orbital motion, i.e., a decrease in the semi-major axis, or deceleration, i.e., an increase in the semi-major axis.

Table 5. The magnitude of the Yarkovsky effect Δ *a* for one revolution of asteroid 2001 CB21 (138971) around the Sun depending on the inclination angle of the asteroid's rotation axis

γ, degrees	0	45	90	135	180
Δa (10^{-12} AU)	0.9044	0.6328	–0.0135	–0.6463	–0.9044

CONCLUSION

In the Pulkovo Observatory of the Russian Academy of Sciences, observations of the potentially hazardous asteroid (138971) 2001 CB21 were conducted in 2022 during its approach to Earth using the ZA-320M telescope. Astrometric and photometric series of asteroid observations were obtained, and an attempt was made to improve its orbit. The circumstances of the asteroid's approaches to Earth and Venus over a 200-year time interval were noted. The nearest close approach of the asteroid to Earth is expected on March 6, 2043. The influence of non-gravitational effects on its orbit was evaluated. Based on photometric observations in the integral band, a light curve of the asteroid was constructed, and the period of its axial rotation (3.305 ± 0.002 h) was confirmed.

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