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Astrometric and Photometric Studies of the Asteroid 2008 TC3

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Abstract—Near real time astrometric and photometric observations of the asteroid 2008 TC3, discovered 19 hours before it fell to Earth in the area of northern Sudan, were conducted on the night of October 6–7, 2008, using an automated telescope ZA-320M of the Pulkovo Observatory. In the interval of 4 h, 270 observations in the integral band of the telescope were performed, which was about one-third of all global observations of the asteroid. Based on the analysis of all cases, physical parameters of the asteroid were assessed. The estimates of the absolute magnitude of the asteroid (M_V = 30.6 ± 0.4 μm), its size (4.8 ± 0.8 m), and weight (131 ± 5 t) were obtained. A frequency analysis of the observational series was conducted, which helped to detect the periodicity in the brightness variation of the asteroid. The elements of the heliocentric orbit of the asteroid were refined. The trajectory of the asteroid, taking into account the atmospheric drag and nonsphericity of the Earth, was simulated.

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INTRODUCTION

On October 6, 2008, at $6^h 39^m$ UTC in the Mount Lemmon Observatory in Arizona, Richard Kowalski, using a 1.5-meter Catalina Sky Survey telescope, discovered a small asteroid approaching Earth (McGaha et al., 2008). The first calculations of its orbit showed that the asteroid would fall to Earth 19 hours after its discovery, presumably in northern Sudan (Jenniskens et al., 2009). By the time that the asteroid entered the Earth's atmosphere, 26 observatories all over the world conducted more than 800 observations of the asteroid, which was named 2008 TC3. A third of them were made on the mirror astrograph ZA-320M at the Pulkovo observatory.

The object entered the atmosphere over the territory of northern Sudan at $02^h 45^m 40^s$ UTC with a relative speed of 12.4 km/s, and five seconds later it exploded in the atmosphere at an altitude of 37 km (Jenniskens et al., 2009; Kwok, 2009). Fragments remaining after the explosion fell to Earth along the trajectory of the body (Jenniskens et al, 2009). During the search for fragments in the predicted fall area, 47 meteorites with a total weight of 3.95 kg were found. Chemical and spectral analysis of the found fragments showed that the meteorites belong to the class of achondrites called urelites. At the same time, the object is abnormal for this class of meteorites; i.e., instead of the usual large-grain structure, a fine-grain structure with large carbon grains is observed. The high metal content and high porosity (25–37% instead of the usual 9%) are also uncommon. Based on the analysis of the found fragments, such important characteristics of the asteroid as the albedo (0.046 ± 0.005) and density (2.3 ± 0.2 g/cm^3) were identified. Spectral analysis also showed that the asteroid belonged to the taxonomic class F (Jenniskens et al., 2009), rare among asteroids coming close to Earth. It should be noted that for the class F, this asteroid is also unusual because the typical value of density for objects of this class is about 1.29–1.38 g/cm (Vinogradova et al., 2003). Among the asteroids coming close to Earth, this asteroid was placed in the Apollo group.

ASTEROID 2008 TC3 OBSERVATIONS AND THEIR ANALYSIS

Over 19 hours since the discovery of the asteroid 2008 TC3 and up to its fall to Earth, 859 observations were made of it in 26 observatories around the world. Figure 1 shows a chart with the number of observations for different observatories. The Pulkovo Observatory made 270 observations (Devyatkin et al., 2009), i.e., almost a third of the total number of observations. The observations were conducted on the mirror astrograph ZA-320M (Deviatkin et al., 2004; Devyatkin et al., 2009). Astrometric and photometric processing of the asteroid 2008 TC3 observations was performed using an APEX-II software system (Devyatkin et al., 2007, 2010). The astrometric coordinates and magnitudes obtained (in the instrumental photometric band of ZA-320M) for the asteroid 2008 TC3 are also available online at http://neopage.pochta.ru/ENG/OBSERVS/2008tc3.txt.

For the photometric analysis of observations, in this study we used three different groups of observations: data received in the integral band of the ZA-320M telescope from the Pulkovo Observatory (Fig. 2), all observations in the *R* filter (Fig. 3), and all observa-

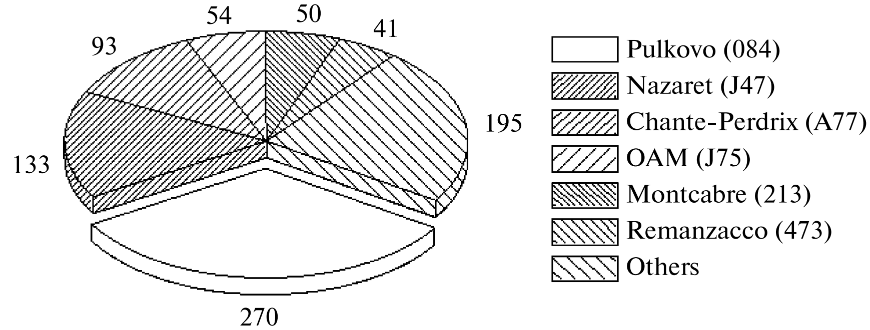

Fig. 1. Number of global observations of the asteroid 2008 TC3.

tions in the V filter (Fig. 4). Based on these observations, we estimated the absolute magnitude H of the asteroid in these bands. In this case, we used the known relationship (Lagerkvist and Williams, 1987):

$$H = m - 5\lg(r\Delta) + 2.5\lg[(1-G)\Phi_1 + G\Phi_2], \quad (1)$$

where $\Phi_i = W\Phi_{iS} + (1 - W)\ \Phi_{iL}$, $i = 1.2$;

$$W = \exp\left(-90.56\tan^2(\alpha/2)\right),$$
$$\Phi_{iS} = 1 - C_i\sin(\alpha)/$$
$$\left(0.119 + 1.341\sin(\alpha) - 0.754\sin^2(\alpha)\right), \quad (2)$$
$$\Phi_{iL} = \exp\left(-A_i\tan(\alpha/2)^{Bi}\right),$$
$$A_1 = 3.332,\ B_1 = 0.631,\ C_1 = 0.986,$$
$$A_2 = 1.862,\ B_2 = 1.218,\ C_2 = 0.238.$$

Here, m is the observed magnitude; r and Δ are the heliocentric and topocentric distances of the object, respectively; Φ_1 and Φ_2 are the functions of the phase angle α; and G is the slope parameter, which is an important photometric characteristic of the object. In the formula (1) there are two unknown quantities, i.e., the absolute magnitude H and the parameter G. Thus, from formulas (1) and (2), provided that there is a sufficient number of observations, both quantities may be obtained by the least squares method. To do this, let us denote the absolute magnitude of the asteroid at a phase angle α through $H_\alpha = m - 5\lg(r\Delta)$. The system of conditional equations for determining H and G is the following:

$$H_{\alpha k} = -2.5\lg[a_1\Phi_{1k} + a_2\Phi_{2k}], \quad k = 1, N, \quad (3)$$

where N is the number of observations, and a_1 and a_2 are the unknown coefficients of the linear system, calculated using the method of least squares. The values H and G are determined from these coefficients as follows (Lagerkvist and Williams, 1987):

$$H = -2.5\lg(a_1 + a_2), \quad G = a_2/(a_1 + a_2). \quad (4)$$

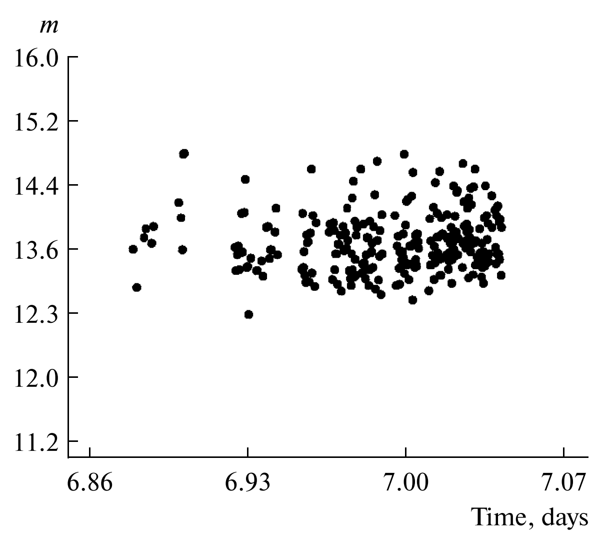

Fig. 2. Photometric observations of the asteroid 2008 TC3 in the integral band, performed at the Pulkovo observatory using the ZA-320M telescope.

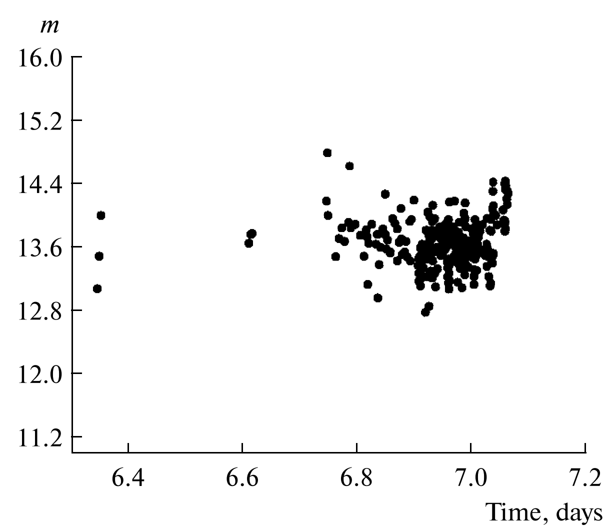

Fig. 3. Photometric observations of the asteroid 2008 TC3, performed in different observatories in the filter R of the UBV photometric system.

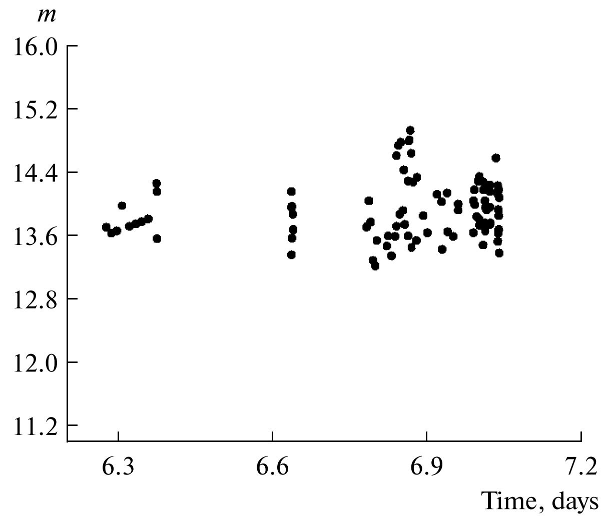

Fig. 4. Photometric observations of the asteroid 2008 TC3, performed in different observatories in the filter *V* of the UBV photometric system.

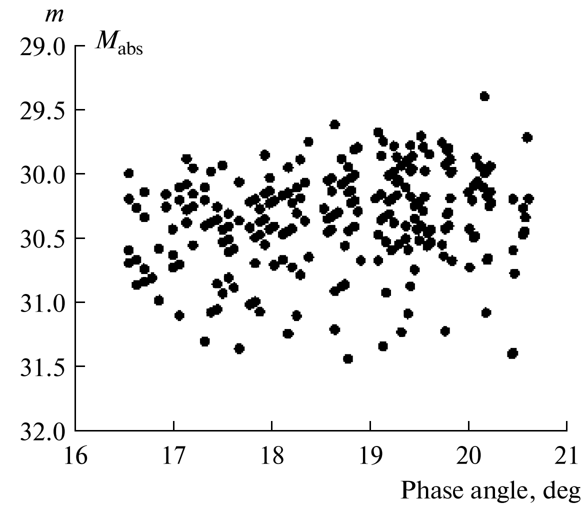

Fig. 5. The dependence of the magnitude on the phase angle for the asteroid 2008 TC3, obtained on the basis of the Pulkovo observations of the integral band.

The results obtained for all three groups of observations, i.e., the world's observations in the filters *V* and *R*, and the Pulkovo observations in the integral band of the telescope, are presented in Table 1. It is obvious that the value of the slope parameter is not significant because of the great mistakes of its definition. This is due to errors of observations and a small range of change of the phase angle from 16.5° to 23°. Therefore, to estimate the absolute magnitude, the average for asteroids of this type value $G = 0.15$ was used (Vinogradova et al., 2003; Jenniskens et al., 2009). For each observation in three groups, values are calculated and averaged according to the formula (1) (Figs. 5–7). From observations using filters *R* and *V* of the UBV photometric system, an estimate of the color index $V - R = +0.3^m$ was received. Mean values of absolute magnitudes and color indices are given in Table 2.

FREQUENCY ANALYSIS OF LIGHT CURVES OF THE ASTEROID 2008 TC3

To detect possible periodicities of the brightness variation of the asteroid 2008 TC3, which might be caused by its rotational motion, the frequency analysis of all three series of observations was conducted. To this end, we used three different methods of frequency analysis: (1) the CLEAN method (Vityazev, 2001a), (2) the Scargle method (Scargle, 1982), and (3) the wavelet analysis (Vityazev, 2001b). All these methods have a different mathematical basis. The CLEAN method is based on the Fourier transformation. The Scargle method is based on the least squares method. In the wavelet analysis, a three–dimensional wavelet function of a special form, is used instead of the Fourier transformation. Therefore, the considered methods may be considered independent and complementary.

Table 1. Results of the determination of the absolute magnitude *H* and the slope parameter *G* of the asteroid 2008 TC3 on the basis of observations

Parameters	Filter *V*	Filter *R*	Integral band (ZA–320M)
H	$31.2^m \pm 2.3^m$	$29.9^m \pm 0.7^m$	$30.3^m \pm 1.4^m$
G	-2.3 ± 5.4	-1.4 ± 1.1	-1.6 ± 2.4

According to (Jenniskens et al., 2009), the object had two periods of 49 and 97 s. Obviously, the second period was a harmonic of the first one. These periods may not be identified from the series of observations for the filters *V* and *R*, because there were intervals of a few minutes between frames. The Pulkovo series of observations was obtained at intervals of 10–20 s between successive frames, which allows us to identify such short periods. Observations were grouped into eight series, within which it was possible to identify common stars in order to use them as a reference for the photometric processing. There were no common reference stars for the entire series of observations, because the object moved fast against the stars. The obtained series of observations were subjected to independent photometric processing. The average accuracy of such processing for different series was 0.05^m. The frequency analysis of each series by three methods showed that a total period of 48.6 ± 0.6 s with the amplitude of $(0.27 \pm 0.08)^m$ is present in all series. This period is consistent with the value obtained in Jenniskens et al., 2009. Thus, we may assume that the

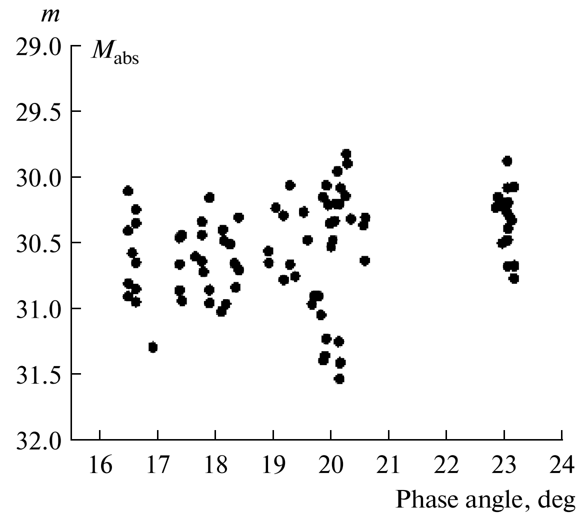

Fig. 6. The dependence of the magnitude on the phase angle for the asteroid 2008 TC3, obtained on the basis of world observations in the filter *V* of the UBV photometric system.

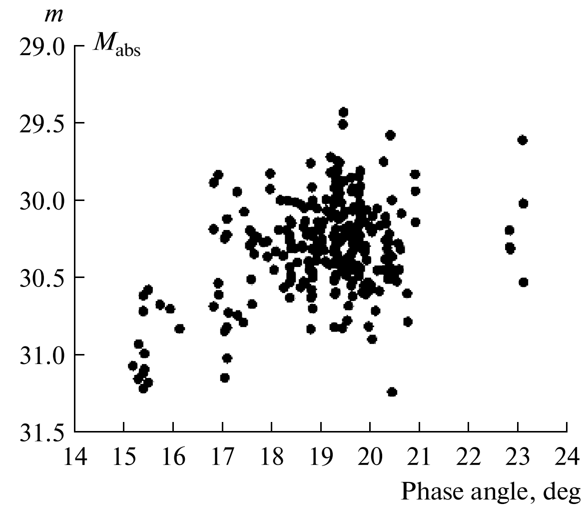

Fig. 7. The dependence of the magnitude on the phase angle for the asteroid 2008 TC3, obtained on the basis of world observations in the filter *R* of the UBV photometric system.

obtained period belonged to the asteroid 2008 TC3, and that it is presumably associated with its axial rotation. If we assume that the asteroid had a symmetrical shape, the period of its axial rotation could be about 97 s.

In addition to the indicated period, other periods with a longer duration present in all three series of observations were detected. Table 3 shows the results of the frequency analysis, conducted by all three methods for different series of observations. It was revealed that in the observations there are periods of 0.287 day (6.89 hr) with an amplitude of 0.2^m and 0.0125 day (18 min) with an amplitude of 0.17^m. In a series of observations for filters *R* and *V*, there are periods of 0.287 day (6.89 hr) and 0.1 day (2.4 hr) with an amplitude of 0.15^m. The last period is a multiple of 24 hrs and may be due to causes unconnected with the observed object. The period of 0.287 day is present in all three series of observations and is detected by all three methods, indicating its authenticity and association with the object. The period of 18 minutes may also be real but not explicitly identified in a series of observations *R* and *V*, because of their high porosity.

ESTIMATES OF POSSIBLE SIZE AND SHAPE OF THE ASTEROID 2008 TC3

Estimates of the asteroid were carried out according to the formula (Vinogradova et al., 2003):

$$\lg(D) = 3.122 - 0.5\lg(p) - 0.2H, \qquad (5)$$

where *H*, *p*, and *D* are the absolute magnitude, albedo, and the diameter of the object, respectively. According to the found asteroid fragments in the band *V*, values of its albedo $p = 0.046 \pm 0.005$ and the average density $\rho = 2.3$ g/cm^3 were identified (Jenniskens et al., 2009). Thus, from (5) and the relation $M = 4\pi R^3\rho/3$, where *R* is the radius of the asteroid, with a known value of *H*, estimates of the diameter *D* and the mass *M* of the asteroid may be obtained.

Our estimate of the absolute stellar magnitude *H* in the filter *V*, assuming that the parameter $G = 0.15$, is $H = +30.6^m$ (Table 2). According to Jenniskens et al., 2009, a similar estimate of the absolute magnitude of the asteroid in the filter *V* is 30.9^m. For available estimate $p = 0.046 \pm 0.005$, the size and mass of the asteroid 2008 TC3 is assessed to be 4.8 ± 0.8 m and 131 ± 5 t, respectively.

As mentioned in the previous section, there was a period of 48.56 s with an amplitude of 0.27^m in the brightness variation of the asteroid. Under the assumption that this period is primary and most important, and is associated with the axial rotation, an estimate of the probable asymmetry of the asteroid was obtained. Let us assume that the shape of the asteroid was a triaxial ellipsoid with semiaxes *a*, *b*, and *c*, where *c* was the smallest semiaxis, corresponding to the smallest axis of inertia, around which the object rotates. During the axial rotation of the object, its brightness changed due to the fact that $a \neq b$, and the

Table 2. Estimates of the absolute magnitude of the asteroid 2008 TC3 for the filters *V* and *R* of the UBV photometric system and for the integral band of the ZA-320M telescope, as well as the color index *V–R*, assuming that the slope parameter is 0.15

Filter *V*	Filter *R*	Integral band	Color index *V–R*
$30.6^m \pm 0.4^m$	$30.3^m \pm 0.3^m$	$30.4^m \pm 0.4^m$	$+0.3^m \pm 0.2^m$

Table 3. The frequency analysis of series of observations of the asteroid 2008 TC3. Periods are given in fractions of days

Type of observation	CLEAN method	Scargle method	Wavelet analysis
All Observatories (filter *R*)	$P_1 = 0.287 \pm 0.005$ $P_2 = 0.09 \pm 0.01$	$P_1 = 0.287 \pm 0.030$ $P_2 = 0.094 \pm 0.004$	$P_1 = 0.287 \pm 0.001$
All Observatories (filter *V*)	$P_1 = 0.287 \pm 0.020$ $P_2 = 0.109 \pm 0.009$	$P_1 = 0.110 \pm 0.018$	$P_1 = 0.287 \pm 0.035$
Pulkovo Observatory	$P_1 = 0.00717 \pm 0.00003$ $P_2 = 0.01255 \pm 0.00005$	$P_1 = 0.00715 \pm 0.00003$ $P_2 = 0.01259 \pm 0.00005$	$P_1 = 0.287 \pm 0.001$

asteroid turned so that we faced one side or another. For a terrestrial observer, the triaxial ellipsoid is projected onto the plane, normal to the line of sight, and thus, in this case, the projection is an ellipse. If $a > b$, then the maximum brightness of the asteroid will match the area of the ellipse, equal to $2\pi ac$, and the minimum brightness will match an area of $2\pi bc$. Using the relation between the magnitude and the luminous flux, we have the following:

$$\Delta m = -2.5\lg(2\pi bc/2\pi ac). \quad (6)$$

Thus, from (6) we obtain $a/b \sim 1.28$.

IMPROVEMENT OF ELEMENTS OF THE HELIOCENTRIC ORBIT OF THE ASTEROID 2008 TC3

To solve this problem, we used a differential method for orbit improvement from the program developed in the Central Astronomical Observatory of the Russian Academy of Sciences, which uses the EPOS software environment (Lviv and Tsekmeyster, 2009; http://neopage.pochta.ru/RUS/ESUPP/main.htm) constants, numerical ephemerides, catalogs of orbits of solar system bodies, etc. The system of elements by the Jet Propulsion Laboratory (JPL), based on 559 observations, was adopted as the initial orbit. Only four observatories other than Pulkovo gave a series of observations from which we may independently improve the orbital elements, even at such a short arc. Improvements were carried out in two ways: based on all available world observations on October 6–7, 2008 (weights were not assigned), borrowed from the NEODys site (http://newton.dm.unipi.it/neodys), and separately on the basis of the Pulkovo series of observations.

Table 4 shows the initial and improved orbital elements for the epoch JD 2454746.5. Figures 8 and 9 show the values of O–C in the right ascension and declination after the improvement of orbits in all the observations.

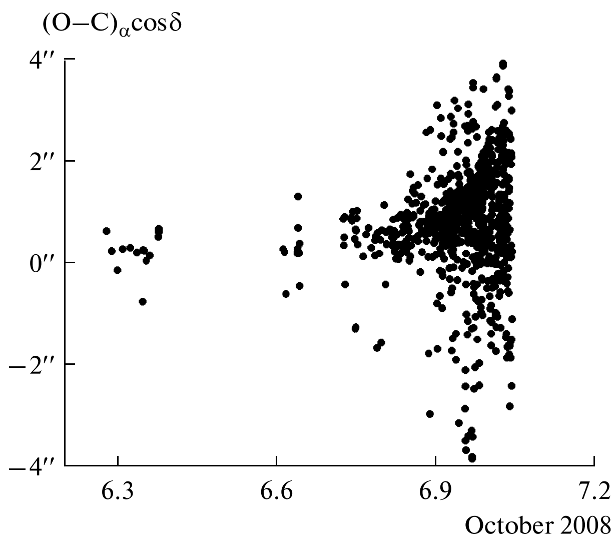

Fig. 8. Values (O–C) in right ascension of the asteroid 2008 TC3.

DESCENT TRAJECTORY MODELING OF THE ASTEROID 2008 TC3

To simulate the trajectory of the asteroid 2008 TC3 the following model was used. If x_0, y_0, z_0, v_{x0}, v_{y0}, and v_{z0} are initial coordinates and velocities at the time t_0 and $t_0 + dt$ is the current point of time, the rectangular coordinates of the object at this point will be determined by the expressions

$$x = x_0 + v_x dt + a_x dt^2/2, \quad y = y_0 + v_y dt + a_y dt^2/2,$$
$$z = z_0 + v_z dt + a_z dt^2/2, \quad (7)$$
$$v_x = v_{x0} + a_x dt, \quad v_y = v_{y0} + a_y dt, \quad v_z = v_{z0} + a_z dt,$$

where a_x, a_y, and a_z are perturbing accelerations. In the model used the acceleration of gravity exerted by the Earth, perturbations from the nonsphericity of the Earth, atmospheric drag, and perturbations from the Moon are taken into account. The integration step in this model is 0.01^s.

Table 4. Elements of the heliocentric orbit of the asteroid 2008 TC3 for the epoch JD 2454746.5

Parameters	JPL	All world observations	Pulkovo observations (ZA-320M)
Number of observations	559	844	257
Mean anomaly, deg	330.754563	330.754607	330.754669
Ascending node—perihelion angle	234.448854	234.448782	234.448676
Longitude of node, deg	194.101138	194.101138	194.101144
Off level, deg	2.542251	2.542248	2.542224
Eccentricity	0.31207056	0.31207056	0.31207057
Semi-major axis, a.u.	1.308210285	1.308210636	1.308211141
Perihelion distance, a.u.	0.899956369	0.899956605	0.899956949
Error of unit weight:			
Before the improvement of the orbit	–	2.08″	26.0″
After the improvement of the orbit	–	1.46″	1.89″

To take into account the nonsphericity of the Earth, the second zonal harmonic was considered, which is on the order of 10^{-3}, while others are on the order of 10^{-6} and above.

In determining the influence of the atmosphere resistance, only the frontal drag was taken into account, which was computed using the following formula (Duboshin, 1971): $R_x = 0.5C_x\rho V^2 S_м$, where C_x is the factor of the aerodynamic drag, $S_м$ is the frontal area, and ρ is the density of air. To determine the density of air at different altitudes, the United States Standard Atmosphere model was used (http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf). It was believed that the asteroid was shaped like a ball.

Perturbations from the Moon were taken into account as follows (m_L is the mass of the Moon):

$$a_{Lx} = -Gm_Lx/r^3,\ a_{Ly} = -Gm_Ly/r^3,\ a_{Lz} = -Gm_Lz/r^3.$$

Thus, the total accelerations were as follows:

$$a_x = -Gmx/r^3 + a_{J2x} + a_{atmx+}\ a_{Lx},$$

$$a_y = -Gmy/r^3 + a_{J2y} + a_{atmy+}\ a_{Ly},$$

$$a_z = -Gmz/r^3 + a_{J2z} + a_{atmz+}\ a_{Lz},$$

where a_{J2} and a_{atm} are the relevant perturbing accelerations due to the nonsphericity of the Earth and the resistance of the atmosphere. Expressions for these accelerations may be found in Beletski, 1965, and Duboshin, 1971.

Knowing the rectangular coordinates of the object at any given time, we may calculate its geographic coordinates, i.e., latitude, longitude, and altitude, relative to the WGS-84 ellipsoid.

Rectangular coordinates of the object were calculated based on the elements of its heliocentric orbit. Results were obtained for three orbit variants: (1) JPL orbits, (2) orbits improved using Pulkovo observations, and (3) orbits refined by all world observations. Coordinates of the asteroid explosion for all three variants are shown in Table 5. The altitude of the explosion was

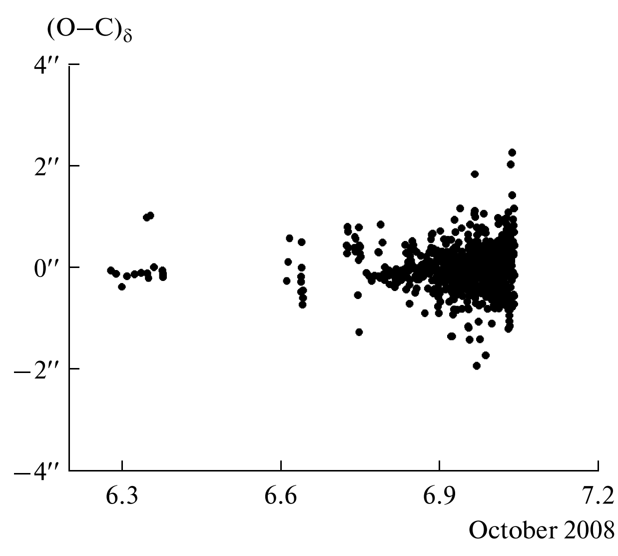

Fig. 9. Values (O–C) in declination of the asteroid 2008 TC3.

Table 5. Geographic coordinates (longitude and latitude) of the explosion point at the altitude of 37 km and a probable fall (0 km) of the asteroid 2008 TC3, calculated using the orbital elements of JPL, as well as the orbits, refined on the basis of the Pulkovo series of observations and the entire world observations. For the altitude of 37 km the coordinates obtained using meteorological data are also given

Altitude, km	JPL	Pulkovo observations (ZA–320M)	All world observations	Meteorological satellite data
37	32.47°E, 20.69°N	32.40°E, 20.76°N	32.29°E, 20.80°N	32.20°E, 20.80°N
0	33.38°E, 20.49°N	33.33°E, 20.56°N	33.19°E, 20.49°N	–

37 km relative to the WGS-84 ellipsoid, in comparison with the data recorded with the help of weather satellites (Kwok, 2009; Jenniskens et al., 2009), as well asthe coordinates of a possible asteroid impact point on the Earth's surface if the explosion had not happened. It is evident that the best result (greatest agreement with the meteorological data) gives a variant of the orbit, improved according to all the worldwide observations.

Figure 10 shows the simulated descent trajectory of the asteroid for this variant. The coordinates obtained at altitudes of 50, 37, and 20 km are also marked on this figure. The corresponding coordinates obtained by meteorological satellites are given in parentheses for comparison. In modeling, we used the size and weight obtained above. Calculations showed that the asteroid entered the Earth's atmosphere at an average speed of 12.8 km/s. The asteroid passed its entire path in the atmosphere, from an altitude of 70 km to the point of the explosion at the altitude of 37 km, in just 8 seconds. Figure 11 shows a map of the crash site of the asteroid in northern Sudan, on which points of the explosion at the altitude of 37 km according to the meteorological data and simulation results are marked. The place where fragments of the asteroid were found and the probable point of the fall of the asteroid if there had not been an explosion are also

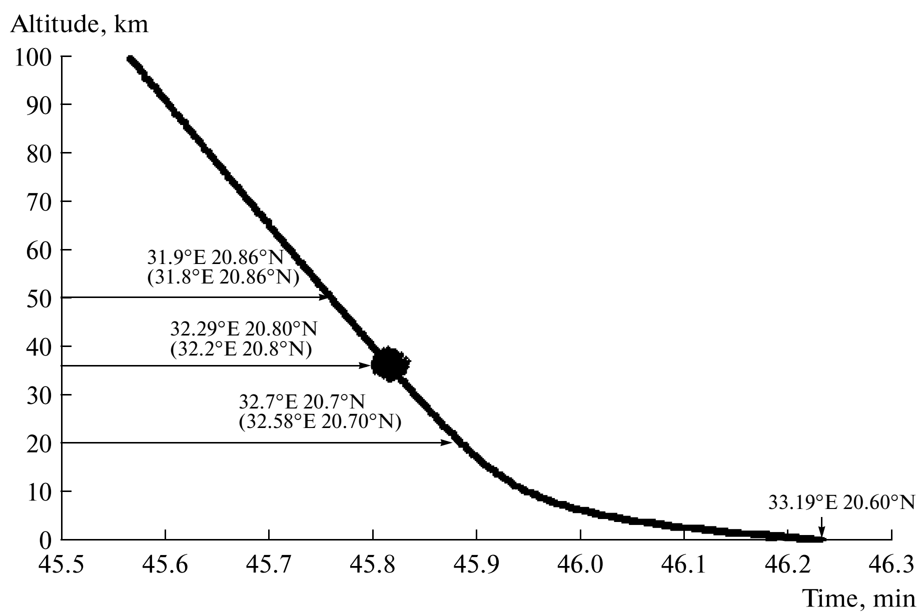

Fig. 10. Estimated descent trajectory of the asteroid 2008 TC3 to the Earth. The vertical axis represents the altitude in kilometers. The horizontal axis represents the moments of time in minutes from 2 h UTC of October 7, 2008. The explosion site at the altitude of 37 km and geographic coordinates (latitude and longitude) of the asteroid at the altitudes of 50, 37, and 20 km are indicated. For comparison, the corresponding coordinate values, recorded by meteorological satellites, are given in parentheses. The coordinates of the probable asteroid impact point in the absence of the explosion are also designated.

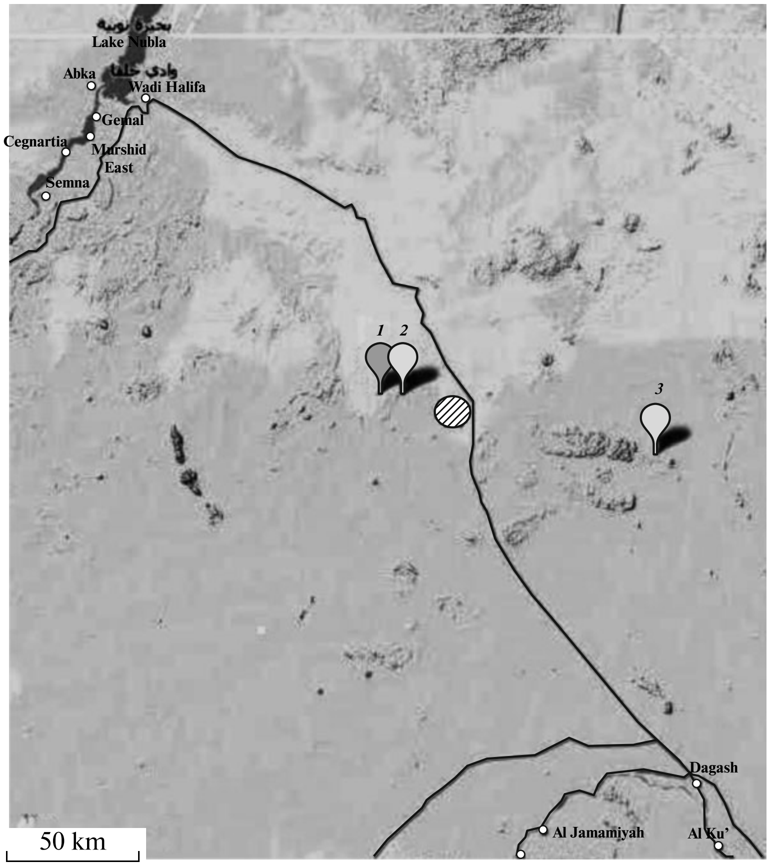

Fig. 11. Map of the asteroid 2008 TC3 impact area. *1* is the site of the asteroid explosion at the altitude of 37 km according to the meteorological satellite, *2* is the location of the asteroid at the altitude of 37 km for the model trajectory, *3* is the location of the asteroid at the altitude of 0 km for the model trajectories assuming that the explosion had not happened. The shaded circle is the impact area of asteroid fragments.

designated. The difference between the calculated place of the explosion and the actual one is 9 km.

CONCLUSIONS

The asteroid 2008 T3C fell to Earth on October 7, 2008. For 19 hours before the crash more than 800 observations of this object were carried out, a third of which were done by the Pulkovo Observatory.

Based on these observations, absolute magnitudes of the asteroid for filters *V* and *R* of the UBV photometric system and for the integral band of the ZA-320M telescope of the Pulkovo Observatory were estimated. Its size and weight were also assessed. The frequency analysis of the obtained series of observations by different methods showed that there were periodicities in brightness variations of the asteroid. This allowed us to estimate the period of the asteroid axial rotation.

With Pulkovo observations of the asteroid and those from the rest of the world, elements of its heliocentric orbit were improved. Using obtained estimates of the size and mass of the asteroid, its descent trajectory to the Earth was simulated.

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