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ИЗВЕСТИЯ

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RESULTS OF PHOTOMETRICAL ANALYSIS OF ASTEROID (3200) PHAETHON

Abstract. We present the results of photometry of the Phaeton asteroid from CCD observations obtained on the Zeiss-1000 telescope of the Tien Shan astrophysical Observatory (TSO) in three Johnson-Cousin filters, B, V and R. The light curves are obtained, the values of the stellar magnitudes in the standard photometric system, as well as the color indices (B-V) and (V-R) are determined. Mean values of stellar magnitudes at unit heliocentric and geocentric distances: M_B=16.306±0.033, M_V=15.75±0.02, M_R=15.36±0.04. The color indices are (B-V) = 0.56 ±0.03, (V-R) = 0.38±0.03. The analysis of differential light curves is carried out by the methods of Phase Dispersion Minimization (PDM), Lomb-Scargle periodogram (LS) and the analysis of combined statistics (Ψ). As a result, the value of the rotation period of the asteroid is determined. Weighted average value of rotational period over three filters and three methods is 3.6042 ± 0.0004 hours.

Key words: Objects: asteroids; observations: CCD observations: data analysis; methods: lightcurve analysis, photometry

Introduction

The Japanese Aerospace Agency (JAXA/ISAS) is developing the DESTINY+ mission (Demonstration and Experiment of Space Technology for INterplanetary voYage, Phaethon fLyby and dUSt science) under which it is planned to launch the PROCYON space module to the Phaethon asteroid in 2022. The purpose of the mission is to conduct detailed studies of the Phaethon dust envelope, its distribution and chemical composition, as well as the analysis of the surface of the asteroid and study its geology. Knowledge of the geology and origin of the Phaethon can shed light on some issues of the formation of the solar system in general and the formation of the Earth in particular. In preparation for this mission, an international campaign to observe the Phaethon from ground-based observatories, organized by the Planetary Exploration Research Center of the Chiba Institute of Technology (Japan), was conducted in 2017. Active participation in this program is taken by the Fesenkov Astrophysical Institute in Kazakhstan (FAI).

Phaethon is the main body of the Geminid meteor stream and has perihelion at just 0.14 a.u., and at aphelion is at 2.4 a.e. The eccentricity of the orbit of 0.89 and inclination of 85°. The period of revolution of the Phaethon around the Sun is 1.4 years. It belongs to near-Earth objects (NEOS), has spectral type B and a diameter of about 5 km (the largest of NEOS at the moment). The Phaethon albedo is known with low accuracy (0.11±0.20), which makes it difficult to obtain an accurate value of its diameter from photometric observations. At the moment of closest approach to the Sun, the surface of the asteroid can be heated up to 1000 K and above. The period of rotation of the Phaeton around its own axis is about 3.6 hours, but requires clarification. The very shape of the asteroid also needs refinement.

The study of the processes of formation and evaporation of dust and small particles from the surface of the asteroid is of great interest, as it is very important to establish a relationship between the Geminid meteor stream and processes occurring on the Phaethon. Some of the meteors of the Geminid stream are large enough to not completely burn out in the atmosphere of the Earth and fall to its surface. Thus the study of the Phaethon is also important from the point of view of assessing the danger of meteorites. For more information on the Phaethon can be obtained from https://ssd.jpl.nasa.gov/horizons.cgi#top (HORIZONS Web-Interface).

Table 1 - Dates of the observations of the Phaethon, used filters and the corresponding exposures

Date	Start (JD)	End (JD)	Filter	Exposure
16.11.2017	2458074.227141	2458074.509545	B,V,R	120, 90, 40
19.11.2017	2458077.218988	2458077.493304	B,V,R	120, 90, 40
20.11.2017	2458078.300265	2458078.442163	B,V,R	120, 90, 40
21.11.2017	2458079.294038	2458079.492062	B,V,R	120, 90, 40
22.11.2017	2458080.291865	2458080.492380	B,V,R	120, 90, 40

Observations

Observations of the Phaethon were carried out at the time of its maximum approach to the Earth in November-December 2017 at the Tien Shan Observatory using two meter-class telescopes "Zeiss-1000", equipped with CCD cameras and a set of filters.

This paper presents the results of the analysis of observations obtained on the telescope "Zeiss-1000-East" equipped with Apogee Alta F16M CCD. The CCD size is 4096×4096 pixels. Observations are made in the second binning, so the size of the resulting image is 2048×2048 pixels. The gain=1.36 and readout noise = 16.07 are determined for this observation mode from the analysis of flat field and bias frames. The scale of the resulting image is 0".56 / pixel, giving a FOV (Field Of View) = 19'.22×19'.22. The observations were carried out sequentially in three Johnson-Cousin filters B, V and R, manufactured by Astrodon. Table 1 provides additional information about observation sessions used in this paper.

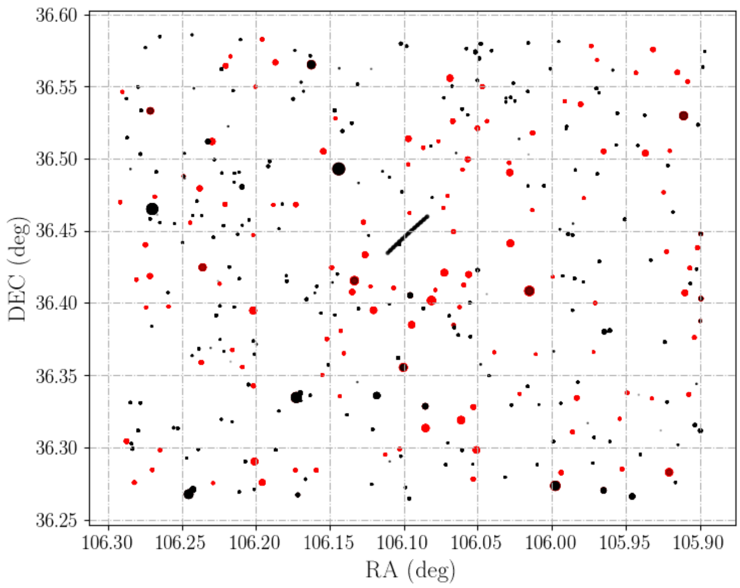


Figure 1 - Map of sources that have passed the procedure of photometry and astrometry. Catalog stars are indicated by colored symbols. Sources not included in the catalog are indicated by black symbols. The size of the symbols depends on the instrumental stellar magnitude. Asteroid track is visible in the center of the frame. The results of observation on 20.11.2017 TSO ("Eastern" Zeiss-1000).

Photometry and astrometry

Evaluation of changes in the values of the coordinates RA and DEC for the longest exposure in the B filter, that is, for 120 seconds, obtained according to the source https://ssd.jpl.nasa.gov/horizons.cgi#top (HORIZONS Web-Interface). These values, ΔRA / 120s = 0".24 and ΔDEC / 120s = 0".56, do not exceed the size of one CCD pixel. For V and R filters, ΔRA and ΔDEC values are even smaller. For astroclimate of TSO with seeing parameter approximately 2".5 - 3".0 it is then possible to consider the PSF profile of the asteroid not very different from the PSF profile of stars and, therefore, the method of photometry procedure described in [1] (the "Method") can be used. At times when the luminosity of the asteroid falls, this technique gives better estimates with fewer errors in both astrometry and photometry. The selection of PSF-photometry is also more reliable in dense stellar fields where it can effectively separate the flux of the asteroid from the flux of the background stars and, thereby, to avoid the gaps in the light curves, which is very critical for accurate determination of the periods of brightness variation of the asteroid.

The output of the Method is a table with the results of photometry and astrometry of the catalog stars and objects that are not included in the catalogs for each CCD frame and for each filter used. To analyze this large array of data, the authors developed software (implemented in python 2.7 under Linux Ubuntu 16.04). The program allows one to construct a map of the location of all sources for which the procedure of photometry and astrometry was carried out successfully. The program automatically saves information in the form of tables for catalog stars and the object selected by the user for further analysis. An example of the resulting map is shown in Figure 1. For sufficiently long observations such a map allows to detect objects with large proper motion. To select out the track of the asteroid, we use the algorithm implemented in *shapely.geometry* method.

Standard field photometry

To convert instrumental stellar magnitudes to the magnitudes in Johnson-Cousins standard photometric system (BVR), observations of the standard fields SA 92 (RA= 00:56:00, DEC=+01:11:00), SA 25 SF3 (RA=06:44:00, DEC=+44:47:00) were made in parallel with the observations of the asteroid. The procedure and parameters of the photometry of the standard stars are similar to the procedure used for photometry of stars on the asteroid field.

The process of transformation to the standard photometric system consists of the following steps. First, the values of instrumental magnitudes taking into account atmospheric extinction are calculated:

$$b_0 = b_{inst} - k_1^B \cdot X_{JD,B}$$
$$v_0 = v_{inst} - k_1^V \cdot X_{JD,V}$$
$$r_0 = r_{inst} - k_1^R \cdot X_{JD,R},$$

where $X_{JD,B}$, $X_{JD,V}$ и $X_{JD,R}$ – airmass at a particular moment of observations for each filter, b_{inst}, v_{inst} and r_{inst} - instrumental stellar magnitude in filters B, V и R, respectively. k_1^B, k_1^V и k_1^R – coefficients of atmospheric extinction in filters B, V and R, respectively. The values of these coefficients can be taken from previous works or determined by the stars of the field of observed objects. In this work, we adopted the following values: k_1^B= 0.2993, k_1^V= 0.2243 and k_1^R= 0.2089. These values were obtained from an analysis of star field for the entire observation period from 16.11.2017, 23.11.2017.

Color indices in the instrumental photometric system are:

$$(b - v)_{obs} = b_0 - v_0$$
$$(v - r)_{obs} = v_0 - r_0$$

The color indices in the standard photometric system and the corresponding errors are expressed by the following dependencies:

$$(B - V)'_{std} = C_3^{(B-V)} \cdot (b - v)_{obs} + C_4^{(B-V)}$$

$$\sigma_{(B-V)'_{std}} = |C_3^{(B-V)} \cdot \sigma_{(b-v)_{obs}}|$$

$$(V-R)'_{std} = C_3^{(V-R)} \cdot (v-r)_{obs} + C_4^{(V-R)}$$

$$\sigma_{(V-R)'_{std}} = |C_3^{(V-R)} \cdot \sigma_{(v-r)_{obs}}|$$

The coefficients $C_i^{C.I.}$ are determined by linear fitting of the corresponding relations.

Stellar magnitudes in the standard photometrical system and corresponding errors can be obtained from the following expressions:

$$B'_{std} = b_0 + C_1^B \cdot (B-V)'_{std} + C_2^B$$

$$\sigma_{B'_{std}} = \sigma_{m_b} + |C_1^B \cdot \sigma_{(B-V)'_{std}}|$$

$$V'_{std} = v_0 + C_1^V \cdot (B-V)'_{std} + C_2^V$$

$$\sigma_{V'_{std}} = \sigma_{m_v} + |C_1^V \cdot \sigma_{(B-V)'_{std}}|$$

$$R'_{std} = r_0 + C_1^R \cdot (V-R)'_{std} + C_2^R$$

$$\sigma_{R'_{std}} = \sigma_{m_r} + |C_1^R \cdot \sigma_{(V-R)'_{std}}|$$

The values of the coefficients $C_i^{B,V,R}$ are determined from the linear approximation of corresponding dependencies. The coefficients obtained by this method are presented in table 1.

Table 1 - The transformation coefficients from the instrumental photometric system to the standard BVR photometric system derived by analysis of observation of the standard fields in the period of 16.11.2017 – 22.11.2017

Date Coeff.	16.11	19.11	20.11	21.11	22.11	Average value
C_1^B	-0.0988	0.1756	0.1674	0.1303	0.1357	0.102±0.046
C_1^V	0.0363	0.0532	0.0317	0.0453	0.0515	0.044±0.004
C_1^R	0.0176	0.2225	0.0027	0.0148	0.0043	0.052±0.038
C_2^B	-2.4222	-2.6725	-2.6363	-2.6573	-2.6631	-2.610±0.042
C_2^V	-2.1382	-2.1918	-2.1718	-2.1625	-2.1727	-2.167±0.008
C_2^R	-2.1485	-2.2737	-2.1870	-2.1707	-2.1676	-2.190±0.020
$C_3^{(B-V)}$	0.893	1.132	1.060	1.083	1.083	1.050±0.037
$C_3^{(V-R)}$	1.0489	0.9276	1.1031	1.1202	1.1266	1.065±0.033
$C_4^{(B-V)}$	-0.2631	-0.5399	-0.4368	-0.5311	-0.5287	-0.460±0.047
$C_4^{(V-R)}$	0.0113	0.0543	-0.0038	-0.0138	-0.0184	0.006±0.012

To exclude the trend in the values of the observed stellar magnitudes due to the change in the mutual distance Asteroid-Earth-Sun, their correction and reduction to the standard distance (to one astronomical unit) are necessary. The value of this correction is computed as:

$$\delta m \equiv H_\lambda - m_\lambda = -5 \cdot log(R_{au} \cdot \Delta_{au}) + 2.5 \cdot log\Phi(\alpha)$$

Here R_{au} and Δ_{au} are heliocentric and geocentric distances to the asteroid. In particular, these heliocentric and geocentric distances at the moment of observations at TSO where determined from https://ssd.jpl.nasa.gov/horizons.cgi#top (HORIZONS Web-Interface) using linear interpolation between the closest moments of time. The phase angle α for the moments of our observations varies from 32° to 31°. In the presented results, $log\Phi(\alpha) = 0$. However, as shown in [2], this assumption can give an error of determining the value of H_R to one magnitude. In this work, we did not take into account the phase correction $\Phi(\alpha)$ because its value is known with a sufficiently low accuracy and in differential photometry, this probably will give second order correction. The obtained values of stellar magnitudes, reduced to unit heliocentric and geocentric distances, as well as the corresponding color indices, are given in table 2. Variations in the values of the color index are mainly due to errors in the determination of transformation coefficients to the standard photometric system and changes in conditions of observations from night to night. In part, these differences can be explained by variations in magnitude with a period slightly shorter than the duration of one observation session, and, as a consequence, not quite correct estimate of the average value.

Table 2 - Values of stellar magnitudes and color indices for each night of observation in the standard photometric system and corrected by δm.

Parameter\Date	16.11	19.11	20.11	21.11	22.11	Simple average	Weighted average
B	16.347	16.377	16.163	16.310	16.335	16.306 ±0.033	---
V	15.818	15.754	15.710	15.715	15.732	15.746±0.018	---
R	15.478	15.418	15.218	15.344	15.361	15.364±0.040	---
$(B-V)$	0.529 ±0.017	0.622 ±0.012	0.453 ±0.013	0.595 ±0.015	0.603 ±0.008	0.560 ±0.028	0.574 ±0.005
$(V-R)$	0.341 ±0.016	0.336 ±0.012	0.492 ±0.018	0.371 ±0.006	0.371 ±0.013	0.382 ±0.025	0.371 ±0.005

Differential lightcurves

To determine the period of changes in the asteroid's brightness caused by its rotation around the axis we analyzed the differential lightcurve calculated as,

$$\overline{\Delta m_{B,V,R}(UT)} = \frac{1}{\sum_{i=1}^{N_{ref}} w^i_{B,V,R}(UT)} \sum_{i=1}^{N_{ref}} \left(m_{B,V,R}(UT) - m^i_{B,V,R}(UT)\right) \cdot w^i_{B,V,R}(UT)$$

Here $m_{B,V,R}(UT)$ – stellar magnitude of the asteroid at particular moment of observation in filter B, V or R, $m^i_{B,V,R}(UT)$ – corresponding magnitude *i*-th reference star, N_{ref} – number of reference stars, and

$w^i_{B,V,R}(UT) = 1/\left(\sigma^i_{B,V,R}(UT)\right)^2$ – weight of each observation and

$\sigma^i_{B,V,R}(UT) = \sqrt{\sigma^2_{m_{B,V,R}}(UT) + \sigma^2_{m^i_{B,V,R}}(UT)}$

$\sigma^2_{m_{B,V,R}}(UT)$ and $\sigma^2_{m^i_{B,V,R}}(UT)$ – error of stellar magnitude of the asteroid and *i*-th reference star at the moment of observation UT in filter B,V and R.

All stars of the field for which there is data in catalogs and for which photometry procedure has been successfully carried out are used as reference stars. Figure 2 shows the values of $\overline{\Delta m_{B,V,R}(UT)}$.

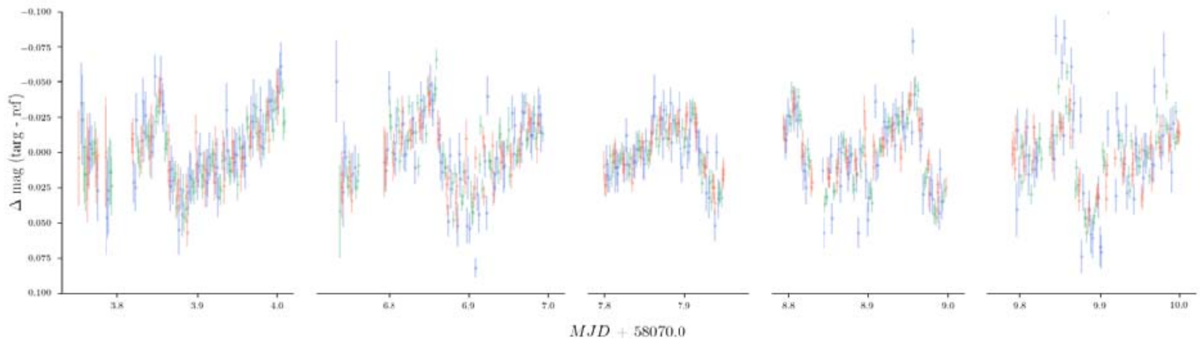


Figure 2 - Differential lightcurve of the Phaethon in different filters (indicated by different colors) based on the results of photometric observations in filters B, V and R, made on the Zeiss-1000 (TSO) in November 2017

Three methods to analyze the variation of $\overline{\Delta m_{B,V,R}(UT)}$ were applied to accurately determine the rotation period of the Phaeton. The first method is based on the analysis of the Lomb-Scargle (LS) periodogram [3]. The second method uses the analysis of the mixed statistics [4],

$$\Psi = \frac{2 \cdot LS}{\Theta}$$

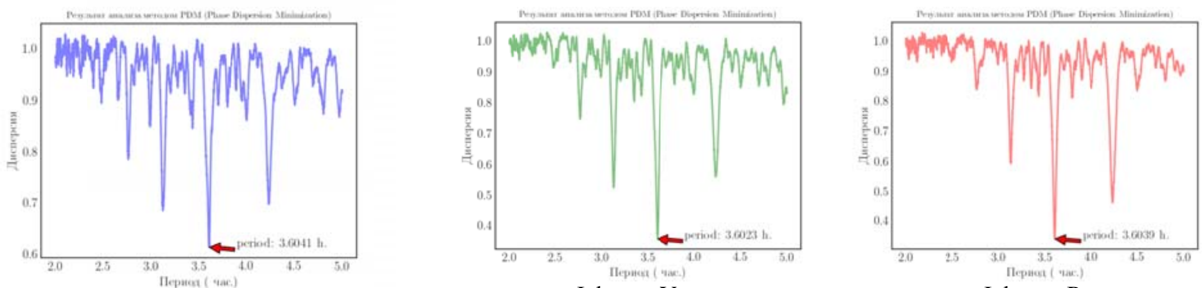
where, LS — value of LS-periodorgam power, a Θ — Lafler-Kinman function [5] of the form:

$$\Theta = \frac{\sum_1^N w_i \cdot \left(\overline{\Delta m_{B,V,R}}^{i} - \overline{\Delta m_{B,V,R}}^{i-1}\right)^2}{\sum_1^N \left(\overline{\Delta m_{B,V,R}}^{i} - \langle \overline{\Delta m_{B,V,R}} \rangle\right)^2 \cdot \sum_1^N w_i}$$

N — total number of observation, $\overline{\Delta m_{B,V,R}}^{i}$ — value of differential magnitude, $w_i = 1/\sigma^2_{\overline{\Delta m_{B,V,R}}^{i}}$ – weight, $\sigma_{\overline{\Delta m_{B,V,R}}^{i}}$ – uncertainty of $\overline{\Delta m_{B,V,R}}^{i}$ value.

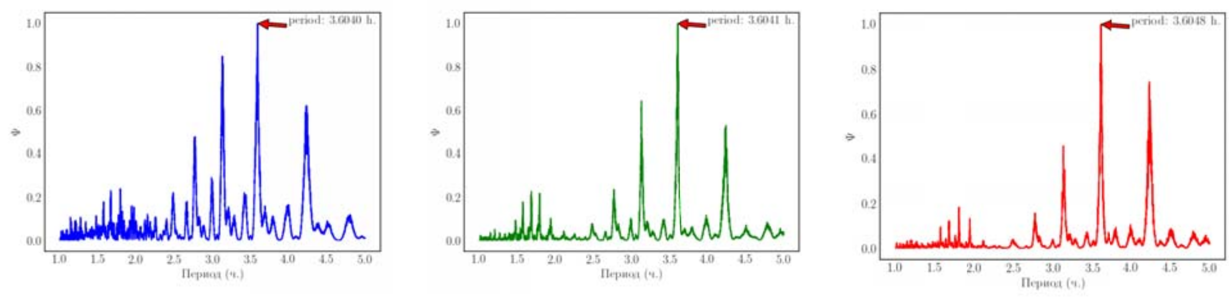
As can be seen in Figure 1, the differential lightcurve of the Phaethon has a rather irregular shape and a third method was used to accurately estimate the period in lightcurve variation (the period of rotation of the asteroid) – the search for the period for the minimum dispersion of the phase curve (PDM – Phase Dispersion Minimization). This method is more adequate for analyzing the variation of an irregular shape, since the algorithm of the method does not depend on the shape of the signal. We use *pyPDM* procedure of the *pyastronomy* package (https://github.com/sczesla/PyAstronomy). The period was searched in the range from 2 to 5 hours with period step of $4 \cdot 10^{-4}$ hours.

The results of PDM method and Ψ-analyzes are shown on figure 3 and on figure 4, respectively.



Johnson B Johnson V Johnson R

Figure 3 - The results of determination of the period of Phaethon's differential magnitude variations in filters B, V and R (designations under the corresponding panels) shown in Figure 2, by the PDM (Phase Dispersion Minimization) method.



Johnson B Johnson V Johnson R

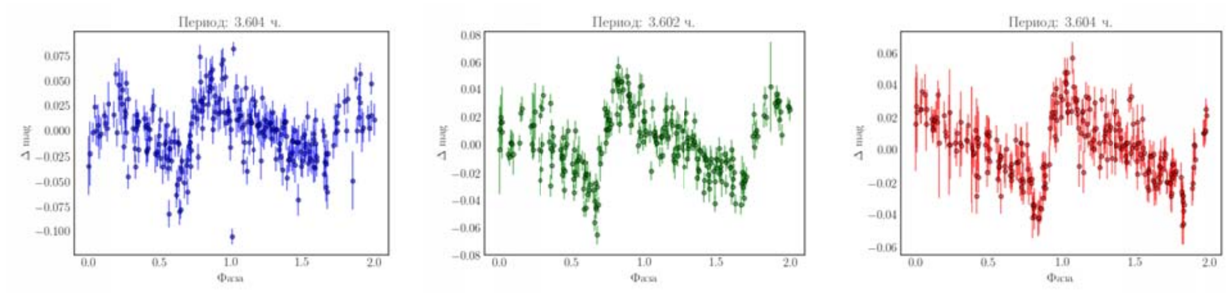
Figure 4 - The results of the determination of the period of the Phaethon magnitude variation in filters B, V and R (designations under the corresponding panels) from the analysis of the combined function Ψ (see text) based on the lightcurve shown in figure 2

Table 3 - The values of the period of Phaethon's magnitude variation in the filters B, V, R, obtained by three methods of analysis of the differential lightcurves, corresponding weighted average of the periods and uncertainty of their determination

Filter \ Method	PDM	LS	Ψ	average
B	3.6041±0.0038	3.6038±0.0012	3.6040±0.0012	3.6039±0.0008
V	3.6023±0.0031	3.6039±0.0011	3.6041±0.0011	3.6039±0.0008
R	3.6039±0.0023	3.6044±0.0010	3.6048±0.0010	3.6045±0.0007
average	3.6035±0.0017	3.6041±0.0006	3.6044±0.0006	3.6041±0.0004 3.6042±0.0004

For each method, the exact position of the maximum (period of magnitude variation) and the corresponding value of error are determined by non-linear approximation of the profile of the peak by a Gaussian function. The obtained period values and corresponding errors for all three methods, for all three filters, as well as the average values obtained as the weighted average and the corresponding error, are shown in table 3.

Figure 5 shows the phase curves obtained by convolution of differential light curves in filters B, V and R with the corresponding periods obtained by PDM



Johnson B Johnson V Johnson R

Figure 5 - Phase curves obtained from differential lightcurves by convolution with the corresponding periods obtained from the analysis using method of PDM (figure 3)

Discussion and Conclusions

Using the results of observations of the Phaethon during its maximum approach to the Earth (16.11.2017-23.11.2017), as well as standard stars for the same period of observations, the values of the color indices of this asteroid were determined: *(B-V) = 0.56 ±0.03* and *(V-R) = 0.38±0.03*. The obtained values are in good agreement with the value *(B-V) = 0.58±0.01* of [6] and with the value *(V-R) = 0.34* of [7], and with the result *(B-V) = 0.59±0.01* and *(V-R) = 0.35±0.01* of [8].

Our results also agree well with the later estimations *(B-V) = 0.62±0.01* and *(V-R) = 0.33±0.06* [9], which were obtained from the observations in the period 2011.11-2012.02. However, our result differs statistically significantly from the values *(B-V) = 0.67±0.02* and *(V-R) = 0.32±0.02* of [2], although the value $M_R = 15.46$ (at α=36°) from the same work is close (within 3σ) to our value *15.364±0.040* (at α=32°).

The relative good agreement of color indices obtained in different epochs of observation suggests that the reflective properties of the surface of the asteroid have not changed much in 2 decades and, perhaps, the assumption that the Phaethon is most likely an "active asteroid", rather than a "dying comet" [10, 12], has its grounds.

From the analysis of differential lightcurves of using three methods, the value of the rotational period of the Phaethon of 3.6042 ± 0.0004 hours is obtained, which is consistent within 1σ range with the result 3.6032±0.0008 hours of [13], but having higher accuracy and is closer to the values of 3.604 of [9] and 3.603958 of [11].

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ФАЭТОН (3200) АСТЕРОИДЫНЫҢ ФОТОМЕТРЛІК ТАЛДАУЛАРЫНЫҢ НӘТИЖЕЛЕРІ

Аннотация. Тянь-Шань астрофизикалық обсерваториясында (ТШАО) Джонсон-Кузиннің B, V және R үш филтрінде «Цейсс-1000» телескобында ЗБА-бақылау мәліметтері бойынша Фаэтон астероидының фотометрлік нәтижелері берілген. Жарқырау қисықтары алынды, стандарттық фотометрлік жүйедегі жұлдыздық шаманың мәндері, сонымен бірге (B-V) және (V-R) түс көрсеткіштері анықталды. Гелиоцентрлік және геоцентрлік бірлік қашықтықтағы жұлдыздық шаманың орташа мәндері: M_B=16.306±0.033, M_V=15.75±0.02, M_R=15.36±0.04. Сәйкесінше түс көрсеткіштері: B-V)=0.56 ±0.03, (V-R)=0.38±0.03. Дифференциалдық жарқырау қисығының талдаулары минимальды дисперсиялы фазалық қисық (PDM), (LS) периодограммасы Ломб-Скаргл (Lomb-Scargle) және (Ψ) аралас статистикалық талдаулар әдістерімен жүзеге асты. Нәтижесінде астероидтың айналу периодының мәні анықталды. Үш әдіс және үш фильтр бойынша айналу периодының орташа өлшенген мәні 3.6042 ± 0.0004 сағат.

Тірек сөздер: Объектілер: астероидтар; бақылаулар; ЗБА-бақылаулары: мәліметтердің талдаулары; әдістер: жарқырау қисықтарының талаулары, фотометрия.

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РЕЗУЛЬТАТЫ ФОТОМЕТРИЧЕСКОГО АНАЛИЗА АСТЕРОИДА ФАЭТОН (3200)

Аннотация. Представлены результаты фотометрии астероида Фаэтон по данным ПЗС-наблюдений на телескопе «Цейсс-1000» Тянь-Шаньской астрофизической обсерватории (ТШАО) в трех фильтрах, B, V и R Джонсона-Кузина. Получены кривые блеска, определены значения звездных величин в стандартной фотометрической системе, а также показатели цвета (B-V) и (V-R). Средние значения звездных величин на единичных гелиоцентрическом и геоцентрическом расстояниях: M_B=16.306±0.033, M_V=15.75±0.02, M_R=15.36±0.04. Соответствующие показатели цвета: (B-V)=0.56 ±0.03, (V-R)=0.38±0.03. Анализ дифференциальных кривых блеска проведен методами минимальных дисперсий фазовой кривой (PDM), Ломб-Скаргл (Lomb-Scargle) периодограммой (LS) и анализом комбинированной статистики (Ψ). В результате определено значение периода вращения астероида. Средневзвешенное значение периода вращения по трем фильтрам и трем методам 3.6042 ± 0.0004 часа.

Ключевые слова: Объекты: астероиды; наблюдения: ПЗС-наблюдения: анализ данных; методы: анализ кривых блеска, фотометрия

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