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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.

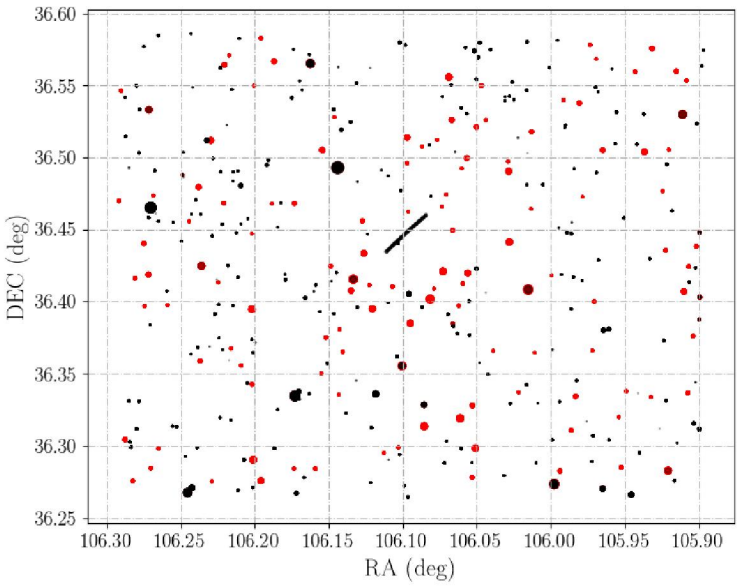

Figure 1 - Map of sources that have passed the procedure of photometry and astrometry. Catalog stars are indicated by colored symbols. Sources not included in the catalog are indicated by black symbols. The size of the symbols depends on the instrumental stellar magnitude. Asteroid track is visible in 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:

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