DOI 10.59277/RoAJ.2023.1-2.09

LIGHTCURVES OF PHAS 2021 HC3, 2001 EC, (7482) 1994 PC1, AND (99942) APOPHIS

ADRIAN SONKA[1], MIREL BIRLAN[1,2], DAN ALIN NEDELCU[1,2], MADALINA TRELIA[1,3]

[1] *Astronomical Institute of Romanian Academy, Str. Cutitul de Argint 5, 040557 Bucharest, Romania*
Email*: adrian.sonka@astro.ro*
[2] *IMCCE, Observatoire de Paris 77 av Denfert Rochereau, 75014 Paris CEDEX, France*
[3] *Faculty of Physics, University of Bucharest, 405, Atomistilor Street, 077125 Magurele, Ilfov, Romania*

Abstract. We present rotational periods of four Potentially Hazardous Asteroids, 2021 HC3, 2001 EC, (7482) 1994 PC1 and (99942) Apophis, from two observatories. From these new CCD observations we derived some information about the internal structure of the asteroids.

Key words: asteroids, minor planets, photometry, NEA.

1. INTRODUCTION

Potentially Hazardous Asteroids (PHAs) are a special group of Near Earth Asteroids (NEAs), defined as large asteroids which could have threatening close approaches to the Earth. Currently asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less are considered PHAs*.

The MOID at a given epoch between two objects orbiting a common primary is the distance between the closest points of their osculating orbits, and is a measure of how close the object can get (Hedo *et al.*, 2020).

The absolute magnitude is a measure of the asteroid size in the absence of a precise direct measurement and it is defined as the visual magnitude an observer would record if the asteroid were placed 1 AU away, and 1 AU from the Sun and at a zero phase angle. Taking into account an albedo of 15%, it is considered that asteroids with sizes larger than 140 m are PHAs.

As a potential threat to human civilisation the PHAs need to be observed constantly in order to establish eventual orbit changes and also to determine their physical properties. The number of PHAs discoveries grows everyday, although the discovery of kilometer sized objects reached a plateau (Figure 1).

Some of the physical properties can be determined by measuring the brightness variation of an asteroid. Usually, from the lightcurve, the rotational period of the object can be determined and if the period is not constant from one cycle to another

*https://cneos.jpl.nasa.gov/about/neo_groups.html

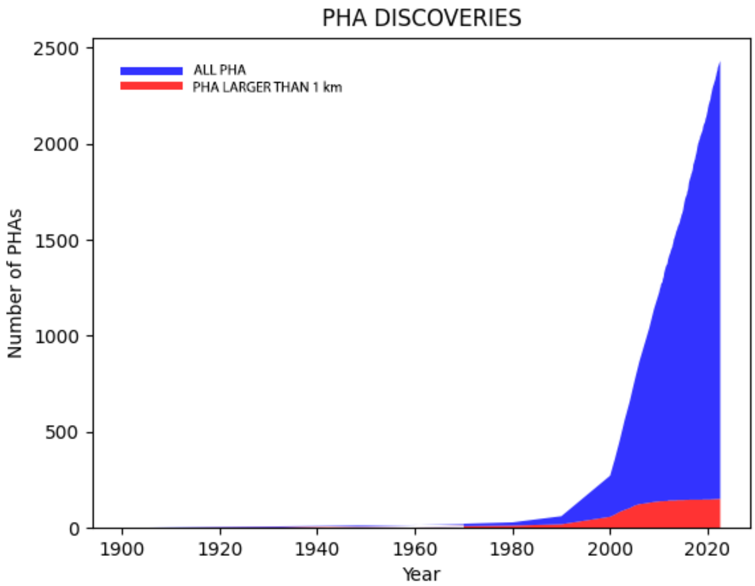

Fig. 1 – PHAs discoveries. While small objects are being discovered in large numbers, the discovery of objects lager than 1km reached a plateau. Data source: Minor Planet Center.

it can be considered that the object is in non-principal axis rotation or a tumbler. The brightness difference between the maximum and the minimum brightness of the lightcurve can be used to establish the axis ratio of the object (Binzel *et al.*, 1989).

The rotational parameters of the asteroids provide information about physical properties such as internal structure and cohesion as well a limit on the density of the object (Pravec and Harris, 2000). From the value of rotational period and using the rotational speed limit discovered by Harris (Harris, 1996), we can estimate if the asteroid has a rubble pile structure or if it has a monolith structure.

Small asteroids ($D < 200$ m) tend to be fast rotators (periods smaller than 2.2 hours) while the large ones tend to have slower spins, a direct indication of their internal structure. Large and slow asteroids are considered rubble pile and could be composed of small and large fragments held together by gravity. Small and fast asteroids are more akin to have a monolithic structure, which allows a fast rotation without breaking up, with the possibility that some are rubble piles where cohesive forces between fragments permit a fast rotation (Polishook *et al.*, 2016).

The Asteroid Lightcurve Database – LCDB (Warner, Harris, and Pravec, 2009), contains data for about 33 959 asteroids (December 2021 version), from which 519 are PHAs. The quality of the rotational period is quantified by the quality code U, the highest being 3 for when the lightcurve is completely unambiguous in terms of

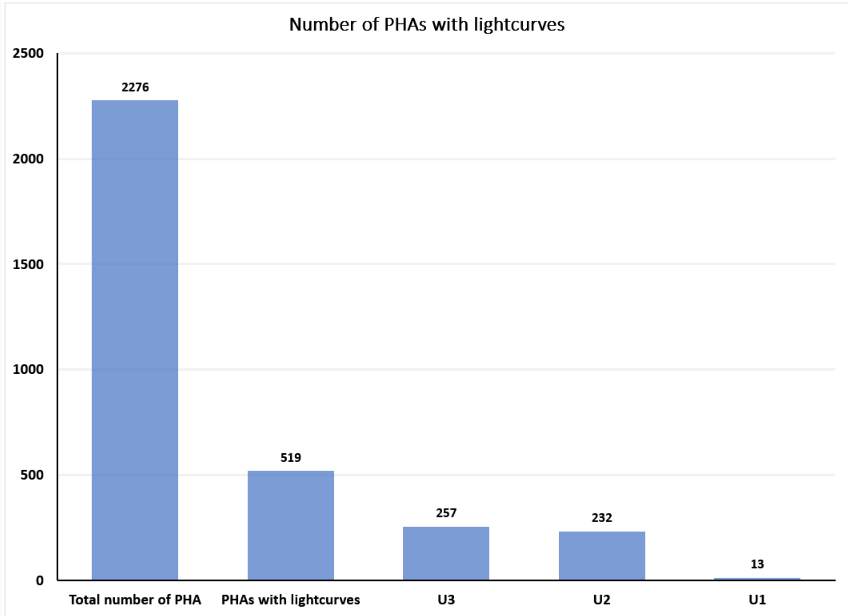

Fig. 2 – Number of PHAs discovered and with lightcurves. Data source: The Asteroid Lightcurve Database, December 2021 version.

period, and the lowest 1-, for a a lightcurve that may be completely wrong and the rotational period very unlikely. From LCDB we find that only 22% of all PHAs have published lightcurves, and only 11% have lightcurves with a unambiguous rotational period (Figure 2).

Observations made at various epochs are also necessary for several reasons, namely: i) when the reconstruction of shape and determination of pole of rotation of an object is needed; ii) when the variation of synodical period due to non-gravitational forces is investigated, iii) to avoid the ambiguity in the rotational period previously determined.

This work tries to improve the knowledge of PHAs by providing rotational periods for PHAs with sizes between 0.15 – 1 km. Four new lightcurves presented in this work are obtained in the frame of long-term project of the Astronomical Institute of the Romanian Academy for monitoring the NEAs population (Sonka *et al.*, 2021b,a; Sonka, Nedelcu, and Birlan, 2022).

2. INSTRUMENTATION, OBSERVATION STRATEGY AND DATA REDUCTION

Observations were carried out with two telescopes of the Astronomical Institute of the Romanian Academy from Bucharest and Berthelot Observatory (Table

Table 1

Instruments used in our observations

Telescope diameter [m]	Type	Camera	Field of View (FoV) [arcmin]	Pixel scale [arcsec/px]
0.50	Riccardi Dall-Kirkham	FLI 16803	36×36	1.07
0.38	Ritchey-Chretien	SBIG STL 11000-M	44×29	1.31

1). Data were obtained using the 0.4 m Ritchey-Chretien telescope (Birlan *et al.*, 2021) with a SBIG STL 11000-M CCD camera, with a pixel array of 4008×2672 pixels, and the 0.5 m Riccardi Dall-Kirkham telescope with a FLI 16803 CCD camera, with a pixel array of $4\,096 \times 4\,096$ pixels – Berthelot Observatory (Trelia *et al.*, 2020; Birlan *et al.*, 2019). Observations were performed in the routinely runs already presented before (Sonka, Gornea, and Birlan, 2018; Sonka *et al.*, 2021b).

Calibration frames were also taken and object images were reduced with dark and flat field frames. For all our targets we acquired unfiltered images with exposure times long enough to ensure a SNR > 10, but short enough to avoid the trailing of the fast moving objects. In the case of asteroids with an unusual high sky motion, we tracked the telescope at half of the differential sky motion in order to obtain trailed sources of light for the asteroid and the reference stars.

Data reduction, photometry and period search were performed with commercial Tycho-Tracker software†. The reference stars were automatically selected by the software, using ATLAS star catalogue (Tonry *et al.*, 2018), with magnitudes in Sloan-r band for reference stars. The magnitudes measurments were transformed to unity, the brightness that the asteroid would have had if it was placed at 1AU from the Sun, and observed from a distance of 1 AU. By placing an object at a standard distance, the reduced magnitude is not influenced by the changing distance between it and the observer. Possible rotational periods were determined using a Fourier Fit of the 2nd degree, which is a very efficient way to calculate the periodogram of unequally spaced data.

3. DATA ANALYSIS AND RESULTS

We present rotational periods of four PHAs (Table 2), determined from observations made in 2021-2022. Two of the observed asteroids (2021 HC3, 2001 EC) do not have any data in literature, while (7482) 1994 PC1 has only one published result. Asteroid (99942) Apophis it is a well studied object because of its close encounter with Earth, in 2029, and its small (but non-zero probability) risk to hit our planet.

Fourier analysis was performed on our data using Tycho Tracker software, with algorithms based on Harris *et al.* (1989). For every set of data we choose a Fourier fit

† https://www.tycho-tracker.com

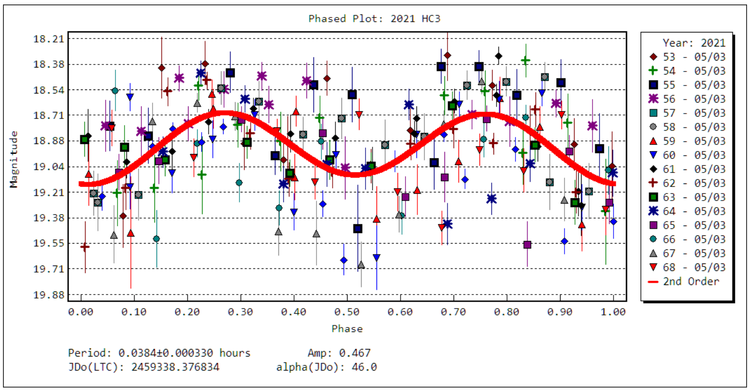

Fig. 3 – Phased lightcurve for 2021 HC3. Data points are coloured as a function of time of observation.

of the second order, specific of ellipsoidal objects. The Fourier analysis provides as a result a rotational period and its error, an epoch of minimum (JD0) and an estimate of the amplitude of brightness variation.

2021 HC3 is small PHA ($\approx$ 140 m) with a close approach on 2021-May-04, at 0.04759 AU. We observed it on the night of May-03, with differential tracking and an exposure time of 10s. Brightness variations were visible as we acquired the data, and confirmed by the Fourier analysis, which shows an amplitude of 0.47 $\pm$0.25 magnitudes on the Fourier fit (Figure 3). In the raw data the amplitude observed reached 0.9 magnitudes.

A rotational period of 0.0384 hours (2.3 $\pm$ 0.0010 minutes) was determined from 225 data points covering a time base over 1.26 hours of observations. We found that 2021 HC3 is a fast rotator with the lightcurve showing minima and maxima, close to the rotational breakup limit for its size. At the time of writing of this article there were no published rotational periods values for this object and our result still needs to be confirmed by other observers.

Asteroid 2001 EC, which passed 0.08149 AU from the Earth on Sep 1, 2021, has an estimated diameter of $\approx$ 650 m. We observed the object on 2021-Sept-05, with 30s exposure, with 3 hours total observing time. Our data shows a low amplitude (0.3$\pm$0.07 magnitudes) light curve, with a possible rotational period of 3.265 hours (Figure 10). However, this result need to be confirmed by future observations, as the total observing time is shorter than the rotational period determined.

(7 482) 1994 PC1 is an interesting object, a large PHA – 1.052 km (Mainzer *et al.*, 2012) with only one result for the lightcurve in the literature. Indeed, Pravec, Wolf, and Šarounová (1998) found in 1998 a rotational period of 2.5999 hours and an amplitude of 0.29 magnitudes. We observed this asteroid on 2022-Jan-18 and 2022-Jan-19, from both observatories, within a time span of 5 and 2 hours respectively, during its close approach with the Earth (0.01325 AU), and we determined a similar

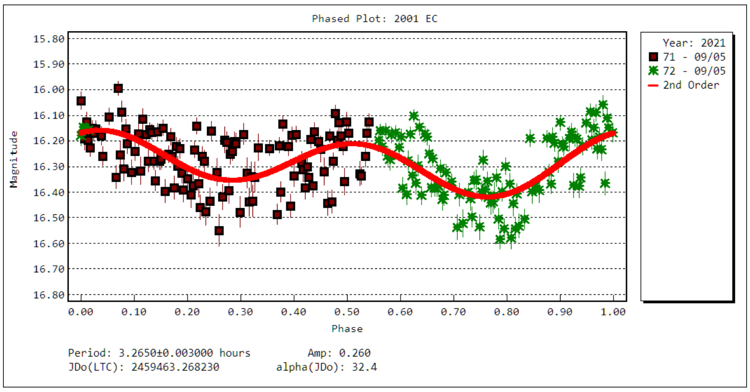

Fig. 4 – Phased lightcurve for 2001 EC. Data points are coloured as a function of time of observation.

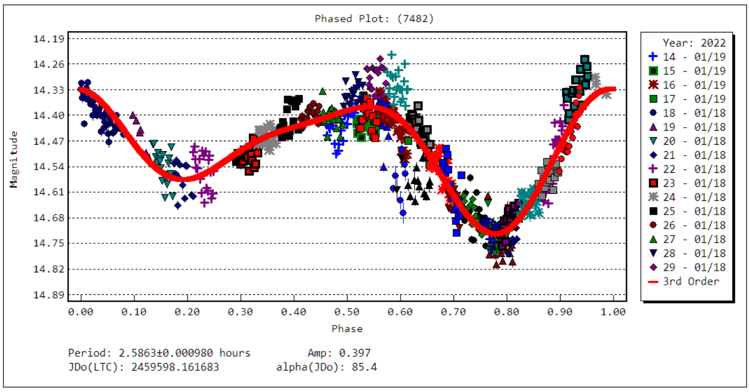

Fig. 5 – Phased lightcurve for (7 482) 1994 PC1. Data points are coloured as a function of time of observation.

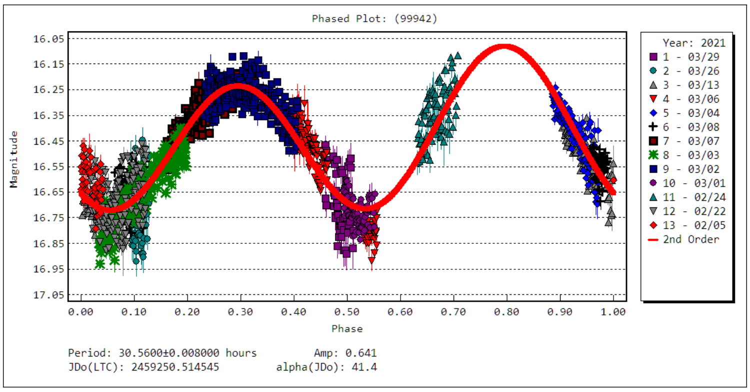

Fig. 6 – Phased lightcurve for (99 942) Apophis. Data points are coloured as a function of time of observation.

Table 2

Determined parameters for the objects observed. P_{rot} is the determined rotational period; $\Delta\ m$ is the amplitude of the brightness variation. ToM is the epoch for a brightness minimum.

Asteroid	P_{rot}[h]	Error [h]	$\Delta\ m$	ToM JD
2021 HC3	0.00384	0.00330	0.47±0.25	2459338.376834
2001 EC	3.2650	0.003	0.26±0.07	2459463.267752
(7482) 1994 PC1	2.5683	0.00980	0.40±0.01	2459598.161683
(99942) Apophis	30.5600	0.008	0.64±0.03	2459250.514545

rotational period similar the one previously established, 2.5683 ± 0.0030 hours, and an amplitude of 0.4±0.01 magnitudes (Figure 11). We found that a Fourier fit of the 3rd degree fitted the observational data better than a 2nd degree one.

We also observed (99 942) Apophis, at its close approach (0.11265 AU) from the Earth, on Mar 13, 2021. We observed this well-known PHA for 13 nights, between February 05 and March 29, with 60s exposure time. We determine a long rotational period of 30.56 hours (Figure 12), in good agreement with previous results (Pravec *et al.*, 2014). The small differences in both the rotational period and the amplitude of the brightness variation (0.64±0.03 magnitudes our result *vs.* 1.14 in literature) can be accounted by the tumbling state of the object (Pravec *et al.*, 2014).

For all the objects we provide periodograms in the Appendix.

Figure 7 presents the diagram diameter versus rotational period for all the asteroids in Lightcurve Data Base (Dec 2021 version), with NEAs marked with blue dots and the asteroids observed by us with red circles. The rotational period limit of 2.2 hours is also plotted. We see that the asteroid 7 482 is a large object, close to the rotational break up speed; 99 942 is a large slow rotating asteroid, while 2021 HS3 is a small fast rotating body, with a possible monolithic internal structure.

The minimum bulk density necessary to withstand a certain spin can be estimated from the following formula (Harris, 1996)

$$\rho_C = \left(\frac{3.3}{P_{rot}}\right)^2 \times \frac{a}{b} = \left(\frac{3.3}{P_{rot}}\right)^2 \times (1+\Delta m) \tag{1}$$

where ρ_C is the bulk density, P_{rot} is the rotational period in hours, a and b are the major and minor axes of the object and Δm is the amplitude of the brightness variation.

In order to make some inferences about the internal structure of the asteroids observed we plotted the spin rate versus the lightcurve amplitude (Figure 8). We find that three asteroids have bulk densities lower than 3 g $\cdot$ cm^{-3}, the higher limit of asteroids with rubble pile structures. 2021 HC3 has a different internal structure which resists the rapid rotation. We note that our result is the first one in the literature and it needs to be confirmed by other observers.

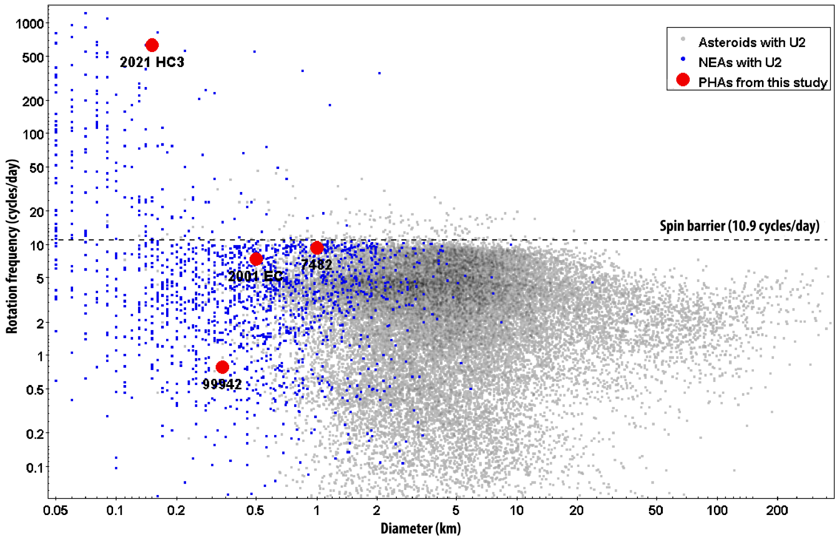

Fig. 7 – Rotational properties for four observed asteroids on the frequency *vs.* diameter diagram for NEAs. Data plotted from LCDB – Dec 2021 version.

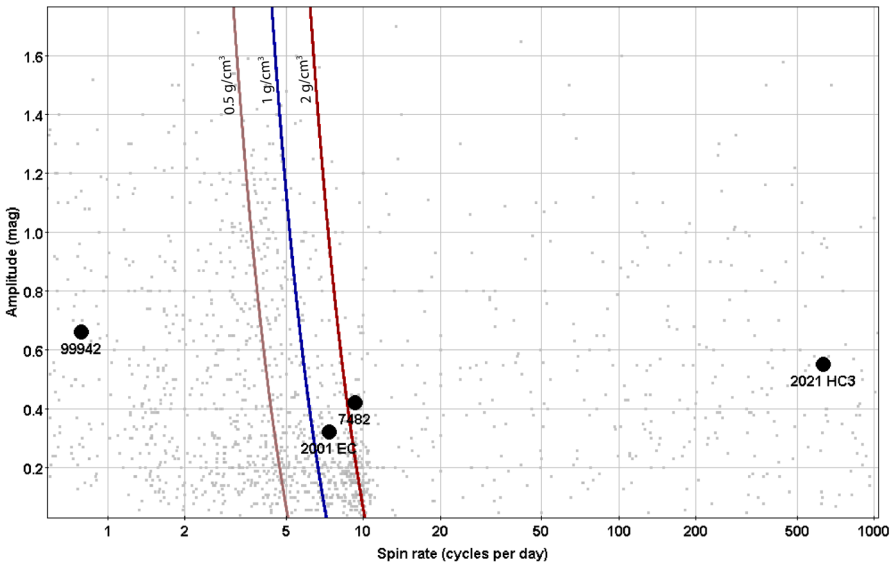

Fig. 8 – Amplitude of brightness variation *vs.* the spin rate of asteroids. Superimposed are the rotational limits (break-up limit) for asteroids with different densities. From this plot we can estimate, in the error limit of our data, a maximum density for the observed asteroids. Data plotted from LCDB - Dec 2021 version.

4. CONCLUSION

In our study we determined values of the rotational period of four Potentially Hazardous Asteroids: 2021 HC3, 2001 EC, (7482) 1994 PC1 and (99942) Apophis, from Berthelot (L54) and Bucharest (073) Observatories. We found a fast rotator (2.3 minutes rotational period), 2021 HC3, with no previous result in the literature (our result still needs to be confirmed by other observers), and one slow rotator, (99942) Apophis, a well studied asteroid, observed during a close approach to the Earth.

We found that (7482) 1994 PC1 is close to the rotational limit for rubble pile asteroids, and 2021 HC3 should have a monolithic structure.

Because the rotation periods give an insight into the body's internal composition, and because Potentially Hazardous Asteroids can, in the future, to impact the Earth, there is an increasing need to characterize these objects, as knowing the internal structure in advance helps to choose mitigation techniques.

APPENDIX

Below we provide periodograms for the asteroids observed. The most likely rotational period is found at the deepest minimum.

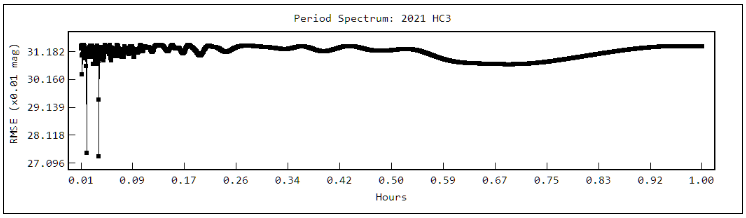

Fig. 9 – Periodogram for 2021 HC3

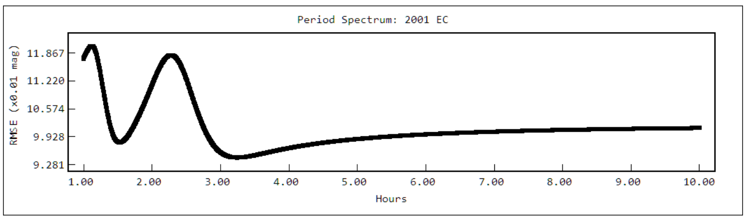

Fig. 10 – Periodogram for 2001 EC.

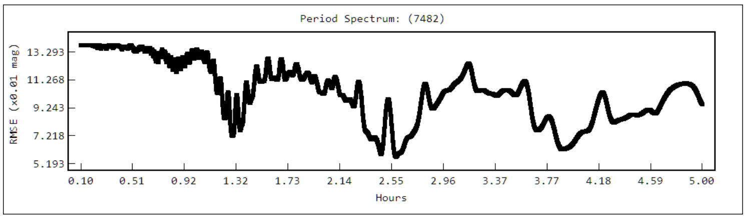

Fig. 11 – Periodogram for (7482) 1994 PC1.

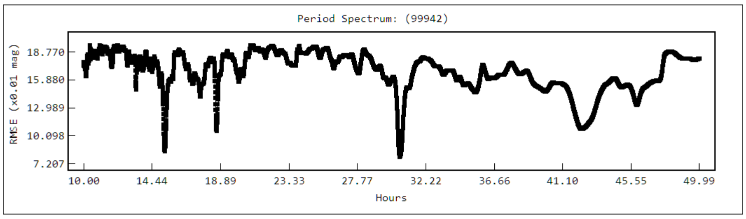

Fig. 12 – Periodogram for (99942) Apophis.

REFERENCES

Binzel, R.P., Farinella, P., Zappala, V., Cellino, A.: 1989, Asteroid rotation rates – Distributions and statistics. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (eds.) *Asteroids II*, 416 – 441.

Birlan, M., Sonka, A., Nedelcu, D.A., Balan, M., Anghel, S., Pandele, C., Trusculescu, M., Dragasanu, C., Plesca, V., Gandescu, C.H., Banica, C., Georgescu, T.: 2019, Telescope calibration for mobile platforms: first results. *Romanian Astronomical Journal* **29**(1), 23 – 32.

Birlan, M., Sonka, A., Badescu, O., Nedelcu, A., Paraschiv, P., Turcu, V., Anghel, S., Besliu-Ionescu, D., Boaca, I., Trelia, M., *et al.*: 2021, Berthelot, the new astronomical station in Romania. *Romanian Astronomical Journal* **31**(1), 41 – 56.

Harris, A.W.: 1996, The Rotation Rates of Very Small Asteroids: Evidence for 'Rubble Pile' Structure. In: *Lunar and Planetary Science Conference*, *Lunar and Planetary Science Conference* **27**, 493.

Harris, A., Young, J., Bowell, E., Martin, L., Millis, R., Poutanen, M., Scaltriti, F., Zappala, V., Schober, H., Debehogne, H., *et al.*: 1989, Photoelectric observations of asteroids 3, 24, 60, 261, and 863. *Icarus* **77**(1), 171 – 186.

Hedo, J.M., Fantino, E., Ruíz, M., Pelaez, J.: 2020, Minimum orbital intersection distance: an asymptotic approach. *Astronomy & Astrophysics* **633**, A22.

Mainzer, A., Grav, T., Masiero, J., Bauer, J., Cutri, R., McMillan, R., Nugent, C., Tholen, D., Walker, R., Wright, E.: 2012, Physical parameters of asteroids estimated from the wise 3-band data and neowise post-cryogenic survey. *The Astrophysical Journal Letters* **760**(1), L12.

Polishook, D., Moskovitz, N., Binzel, R., Burt, B., DeMeo, F., Hinkle, M., Lockhart, M., Mommert, M., Person, M., Thirouin, A., Thomas, C., Trilling, D., Willman, M., Aharonson, O.: 2016, A 2km-size asteroid challenging the rubble-pile spin barrier - a case for cohesion. *Icarus* **267**, 243 – 254.

Pravec, P., Harris, A.W.: 2000, Fast and Slow Rotation of Asteroids. *Icarus* **148**, 12 – 20.

Pravec, P., Scheirich, P., Ďurech, J., Pollock, J., Kušnirák, P., Hornoch, K., Galad, A., Vokrouhlickỳ, D., Harris, A., Jehin, E., *et al.*: 2014, The tumbling spin state of (99942) apophis. *Icarus* **233**, 48 – 60.

Pravec, P., Wolf, M., Šarounová, L.: 1998, Lightcurves of 26 near-earth asteroids. *Icarus* **136**(1), 124 – 153.

Sonka, A., Birlan, M., Nedelcu, D.A., Badescu, O., Henriksen, A.I.: 2021a, Photometric observations of Low Delta v asteroids. *Romanian Astronomical Journal* **31**(3), 293 – 302.

Sonka, A.B., Gornea, A.I., Birlan, M.: 2018, Photometric Monitoring of PHA (3122) Florence. *Romanian Astronomical Journal* **28**(2), 79 – 86.

Sonka, A.B., Nedelcu, A., Birlan, M.: 2022, Rotational Period of Small NEA 2022 KK5. *Minor Planet Bulletin* **49**(4), 258 – 259.

Sonka, A.B., Turcu, V., Nedelcu, A., Birlan, M., Moldovan, D.: 2021b, Fast Rotator Minor Planet 2020 UA From Cluj and Berthelot Observatory. *Minor Planet Bulletin* **48**(2), 100 – 101.

Tonry, J., Denneau, L., Flewelling, H., Heinze, A., Onken, C., Smartt, S.J., Stalder, B., Weiland, H., Wolf, C.: 2018, The atlas all-sky stellar reference catalog. *The Astrophysical Journal* **867**(2), 105.

Trelia, M., Nedelcu, D., Sonka, A., Birlan, M.: 2020, Estimation of distortion on NEEMO system of telescopes. *Romanian Astronomical Journal* **30**(3), 177 – 185.

Warner, B.D., Harris, A.W., Pravec, P.: 2009, The asteroid lightcurve database. *Icarus* **202**, 134 – 146.

Received on 20 mai 2023