DOI 10.59277/RoAJ.2025.1-2.01

LIGHTCURVES OF NEAR EARTH ASTEROIDS 2024 RJ2, 2024 MK, (363027) 1998 ST27, 2024 PF6, AND (163692) 2003 CY18

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Abstract. We present new CCD observations on five Near Earth Asteroids, 2024 RJ2, 2024 MK, 2024 PF6, (363027) 1998 ST27 and (163692) 2003 CY18, from Berthelot and Bucharest observatories, which allow us to estimate their rotational periods as well as to derive some information on their internal structure. The available astrometric data (optical and radar) was used to perform an orbit computation with the aim of detecting non-gravitational acceleration.

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

1. INTRODUCTION

Near-Earth Asteroids (NEAs) are objects with orbits close to or intersecting the Earth orbit, posing as a threat to human civilization. Currently, more 36 000 NEAs are discovered and more are being discovered every month.

Asteroid orbits, including NEAs, can be found on the Jet Propulsion Lab's Solar System Dynamics site (https://ssd.jpl.nasa.gov), where one can verify past and future positions of every solar system object discovered. Small and medium sized NEAs can be properly observed only during their close approach, when they become bright enough for photometric studies.

In addition to orbital data, Solar System Dynamics provides physical data for asteroids. Information about the spectral type, size, and rotational period is included, all linked from specialized databases. Of special interest for our team are the rotational parameters of NEAs, *e.g.* the rotational period and the amplitude of brightness variation, data which can be used to infer the internal structure of the asteroids.

The brightness variability of the object allows us to estimate its rotational period, and the variation in the rotational period indicates that the asteroid is in non-principal axis rotation (a tumbler). We can also use the amplitude of the brightness variation to estimate the axis ratio of the object (Binzel *et al.*, 1989).

Pravec and Harris (2000) showed that asteroids larger than a few hundred meters rotate slower than 2.2 h, an indication that large asteroids tend to have a rubble-pile internal structure, composed of small and large fragments held together by gravity and, while smaller asteroids, which can rotate faster, are of monoliths.

We aim to plot the distribution of rotational speed vs. size for our sample, in order to see if some of the objects can overcome the so-called spin barrier limit of 2.2 hours. In our study we used and compared with our data the rotational periods found in the Asteroid Lightcurve Database (LCDB, https://minplanobs.org/mpinfo/php/lcdb.php), where we find data for 34 727 asteroids and comets (on the October 01, 2023 version) (Warner, Harris, and Pravec, 2009). It is also worth mention that the rotational period is known to a good degree for only 2 178 near-Earth asteroids, and for only 929 it is known with a high degree of precision, which means that more data are needed, especially in the case of asteroids which are a possible threat to our civilization, as the size and internal structure are important characteristics to know in the event of an impact or a asteroid deflect space mission.

This aim of this work is to improve the knowledge of NEAs by providing rotational periods for five objects. The lightcurves presented in this work are obtained in the framework of a long-term project of the Astronomical Institute of the Romanian Academy to monitor the NEA population (Birlan *et al.*, 2021).

We present rotational periods of five NEAs (Table 2), determined from observations made in 2022-2024, a short analysis of their distribution of rotational periods, and a search for the Yarkovsky signature in the astrometric data.

Three of the observed asteroids (2024 RJ2, 2024 MK, 2024 PF6) do not have any data in the literature. 2024 MK was observed by The Deep Space Network's 230-foot (70-meter) Goldstone Solar System Radar on June 30, and it was discovered that it is in non-principal axis rotation (a tumbler). Unfortunately, no estimate of the rotational period was provided after the radar observation.

(163692) 2003 CY18 has only one published result by Warner and Stephens (2022), who found that a single-period solution for its rotation does not work. They estimated a rotational period of 27.66 hours and an amplitude of the light curve of 1.22 magnitudes.

Asteroid (363027) 1998 ST27 rotational period is known to be 3 hours, a result based on less than full coverage, so that the period may be wrong by 30% or so, and no information about its amplitude is given in the literature. In 2001 the asteroid was observed by RADAR from the Arecibo Observatory (http://www.cbat.eps.harvard.edu/iauc/07700/07730.html), and it was determined that it has a satellite.

Anisotropic radiation due to sunlight absorption and delayed thermal re-emision on a rotating body decreases the semi-major axis of retrograde rotators or, alternatively, increases the semi-major axis of prograde asteroids. This effect – the diurnal Yarkovsky effect – was first detected on the asteroid (6489) Golevka, a 530 m diameter PHA, using radar data obtained during multiple close approaches (Chesley *et al.*, 2003).

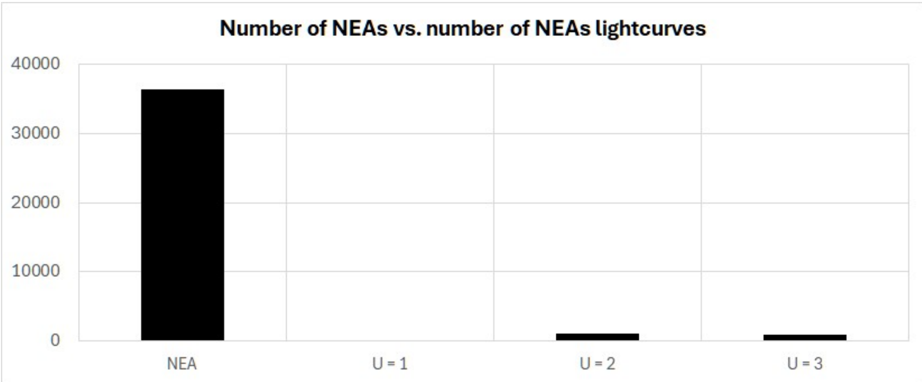

Fig. 1 – Number of NEAs discovered and with lightcurves. Data source: The Asteroid Lightcurve Database, October 2023 version. The quality of the rotational period is quantified by the quality code U, the highest being 3 for when the lightcurve is completely unambiguous in terms of period, and the lowest 1-, for a a lightcurve that may be completely wrong and the rotational period very unlikely.

The diurnal Yarkovsky effect depends on both physical parameters (diameter, thermal inertia, density, shape) and dynamical parameters (rotation period, obliquity, semi-major axis) (Bottke *et al.*, 2006). A long astrometric timespan, preferably including precise radar data (range and range rate) allows the direct detection of Yarkovsky effect in the framework of a precise mathematical model of asteroids dynamic.

2. INSTRUMENTATION AND DATA ANALYSIS

Observations were carried out with two telescopes of the Astronomical Institute of the Romanian Academy from Bucharest and Berthelot Observatory (Table 1). Data were obtained using the 0.5 m Riccardi Dall-Kirkham F/7 telescope with a SBIG STXL-6303 3 CCD camera, with a pixel array of 3072×2048 pixels, and the 0.5 m Riccardi Dall-Kirkham telescope with a FLI 16803 CCD camera, with a pixel array of 4096×4096 pixels for the Bucharest Observatory (Trelia *et al.*, 2020). All observations were made in binning mode 2×2 with both cameras.

Data reduction (dark, flat, and bias subtraction), photometry, and period search were performed with commercial Tycho-Tracker software (https://www.tycho-tracker.com). The reference stars were automatically selected by the software, using the ATLAS star catalogue (Tonry *et al.*, 2018), with magnitudes in the Sloan-r band for reference stars. The magnitude measurements were transformed to unity (Sonka *et al.*, 2023). Rotational periods were determined using Tycho-Tracker period search routines (Harris *et al.*, 1989).

For fast moving asteroids 2024 RJ2, 2024 MK, 2024 PF6 and (363027) 1998

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
0.50	Riccardi Dall-Kirkham	SBIG STXL-6303 3	27×18	1.07

ST27 we had to track the object, while the stars were recorded as short trails. In those cases, we used an elliptical aperture photometry shape for reference stars. The exposure times ranged from 2 to 90 s, depending on the apparent speed of the asteroids.

3. RESULTS

2024 RJ2 is an asteroid discovered on September 3, 2024 by the Asteroid Terrestrial-Impact Last Alert System (ATLAS), just two days before a close approach (0.02709 AU). It is an asteroid with an absolute magnitude of 25.5, which gives a diameter of ∼60 m, assuming an albedo of 0.2. It was observed on night 5/6 September 2024 from Berthelot Observatory.

Our analysis of the data, using a third-order fitting, shows a rotational period of only 0.0379±0.003 hours and an amplitude of 0.617 magnitudes (Figure 2). Although our observation time base is larger than the rotational period, more data is needed to confirm our result. Until November 2024 there are no published results for this asteroid.

2024 MK was discovered on June 16, 2024 by Asteroid Terrestrial-impact Last Alert System (ATLAS). On June 29, 2024 the object had a close approach with the Earth of only 0.00197 AU (294 700 km), during which attained magnitude 11. 2024 MK is a 150 m asteroid, and the close approach was an opportunity to study such a large body.

We observed the asteroid on the night of June 29, from Berthelot Observatory, during its close approach.

The raw light curve of 2024 MK suggests that the object is in non-principal axis (NPA) rotational motion. The tumbling can be recognized by the alternative minima and maxima of uneven depth. In this case, we proceeded to determine a primary rotational period (Period 1) and also a secondary period. We used Tycho Tracker Dual Period Manager. After the primary rotational period was determined, we applied Fourier series analysis to the data with Period 1 subtracted. After the secondary period was determined (Period 2), we refined Period 1 by applying Fourier series analysis on the data with Period 2 subtracted (Figure 3).

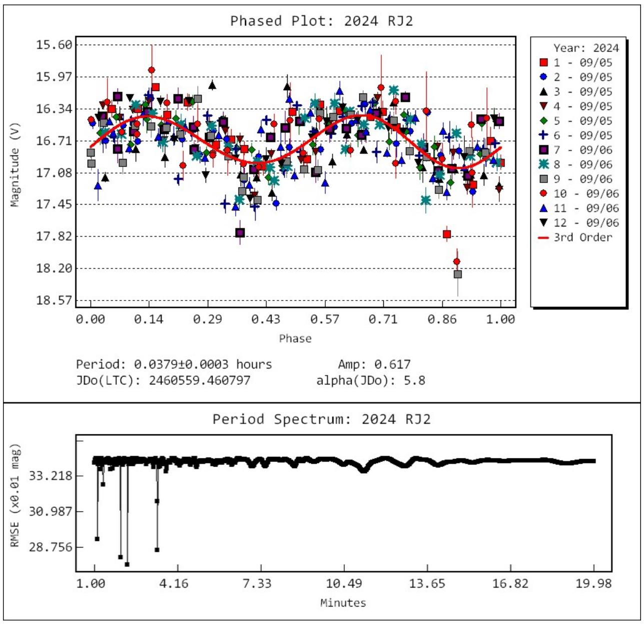

Fig. 2 – Lightcurve and periodogram for 2024 RJ2.

The primary rotational period found is 0.502±0.002 h, with an amplitude of 0.687 mag. The secondary rotational period is 0.334±0.002 h, with an amplitude of 0.438 mag. Until November 2024 there are no published results for this asteroid.

2024 PF6 is an Amor-type near-Earth asteroid that approached Earth on August 13, 2024, at 0.00812 AU (3.161 lunar distances). It was the closest approach recorded for this asteroid. It has an absolute magnitude of 25.2, which indicates an 30 m body. At the time of writing this article there are no recorded lightcurves for 2024 PF6 in the literature.

We observed the asteroid on the night of its closest approach from Berthelot Observatory. Our data show a lightcurve with a rotational period of 2.314±0.009 h and an amplitude of 0.39 mag. Our data allowed us to sample only two rotations. It should be noted that the lightcurve has uneven maxima (Figure 4).

(163692) 2003 CY18 is a ∼700 m asteroid (absolute magnitude 18.26), observed from Bucharest Observatory on May 2022, during 8 nights. It has periodic close approaches at 0.91 AU with Earth every 30 years. The next good observing window for this object will come in August 2054. Our observations, which span 8 nights, began 20 days before the closest approach and ended 11 days after. Our data show two possible rotational periods and a large amplitude of brightness variation, though not as large as the one reported by Warner and Stephens (2022).

A rotational period that matches our data is 27.63±0.02 hours, almost identical

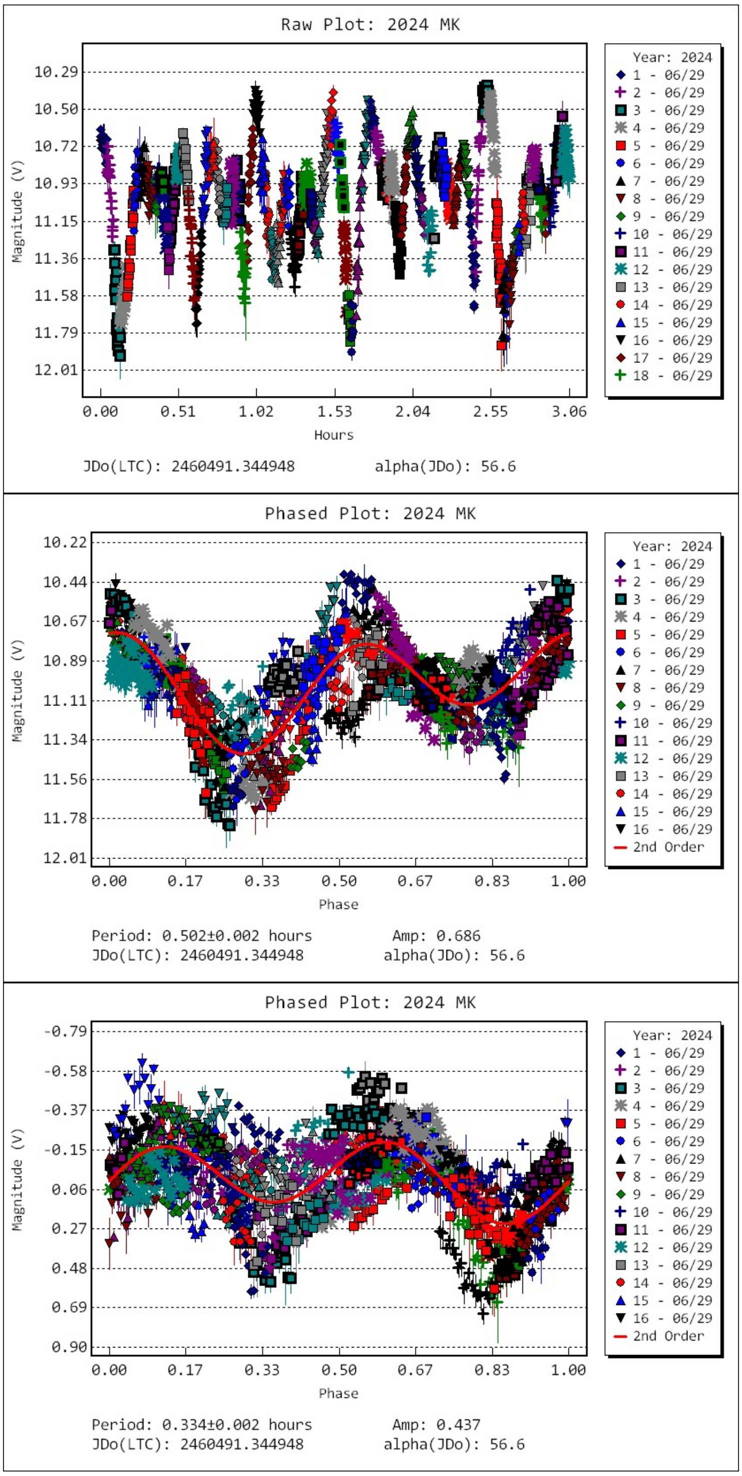

Fig. 3 – Lightcurves for 2024 MK.

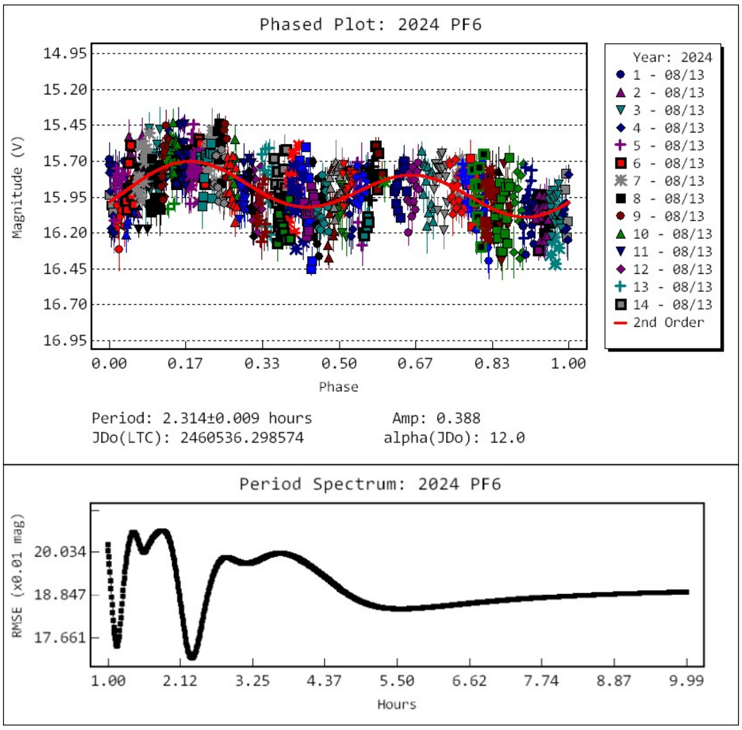

Fig. 4 – Lightcurve and periodogram for 2024 PF6.

Table 2

Determined parameters for the objects observed. P_{rot} is the determined rotational period; Amplitude is the amplitude of the brightness variation, ToM is the epoch for a brightness minimum, exposure time is the exposure time used and total time observed show the number of hours for which the asteroid was observed

Asteroid	P_{rot} [h]	Amplitude [mag]	ToM	Exposure time [s]	Total time observed [h]
2024 RJ2	0.0379±0.0003	0.6170±0.05	2460559.460797	20	2.3
2024 MK Per 1	0.502±0.002	0.6866±0.05	2460491.344948	2	2.9
2024 MK Per 2	0.334±0.002	0.4375±0.05	2460491.344948	2	2.9
2024 PF6	2.314±0.009	0.3885±0.05	2460536.298574	10	5
(363027) 1998 ST27 -	< 0.1	-	-	30 - 60	16.1
(163692) 2003 CY18	27.63±0.02	0.8239±0.1	2459711.319184	90	30.1

to that reported by Warner and Stephens (2022). In this case, our data do not fully cover the maxima of the light curve. Another rotational period that fits a bimodal lightcurve is 17.54±0.02 hours, the case in which our observations cover almost all the lightcurve (Figure 5). In both cases, the amplitude of the brightness variation is 0.8 magnitudes. However, our data are noisier because they were gathered in a light-polluted sky.

(363027) 1998 ST27 is a PHA with a diameter of 578 m, which on October 12, 2024 had the closest approach to Earth of the current century. It attained magnitude 11 while it passed 0.02380 AU from Earth.

We observed the asteroid on 7, 8, 9 and 10 October 2024, two days before its closest approach. From our data a rotational period could not be found because the brightness of the asteroid showed little variation.

Our longest observing run consisted of 5.25 hours of continuous data, and no variation greater than 0.1 magnitude was observed (Figure 6). This indicates a spherical body or a rotation viewed from the pole direction.

Figure 7 presents the rotational period and estimated size for all asteroids in the LCDB (Oct 2023 version), with NEAs (blue dots) and the observed asteroids in this study (black circles). We note that the sizes are estimated using the absolute magnitude. The spin barrier at 2.2 hours, that is, 10.91 cycles/day for large asteroids, is also plotted. From our sample, only 2024 RJ and 2024 MK rotate faster, indicating a monolithic structure or a rubble-pile structure with strong cohesion forces.

The minimum bulk density necessary to withstand a certain spin was presented in more detail by Harris (1996). The plot of spin rate versus lightcurve amplitude (Figure 8) is very useful for the estimation of bulk densities. We find that two asteroids could have bulk densities higher than 3 gcm^{-3}, the highest limit for asteroids with rubble pile structures. Because we do not have references in the literature, our results need to be confirmed by other observers.

Among our targets, 2022 4RJ and 2024 PF6 have a data-span arc of only 9 days, respectively, 3 days. 2024 MK, 2003 CY18 and 1998 ST27 have longer observed arcs of 10.54, 21.82 and 26.06 years.

We modeled the diurnal Yarkovsky effect as a transversal acceleration:

$$a_t = A_2(1/r)^2, \tag{1}$$

where A_2 is the Yarkovsky parameter and r is the heliocentric distance of the asteroid (Farnocchia *et al.*, 2013).

Orbit determination was performed using Phymera (Physical Ephemeris of Asteroids) software developed at the Astronomical Institute (Nedelcu, work in preparation).

In the case of 1998ST27, we detected a clear Yarkovsky signal in the astro-

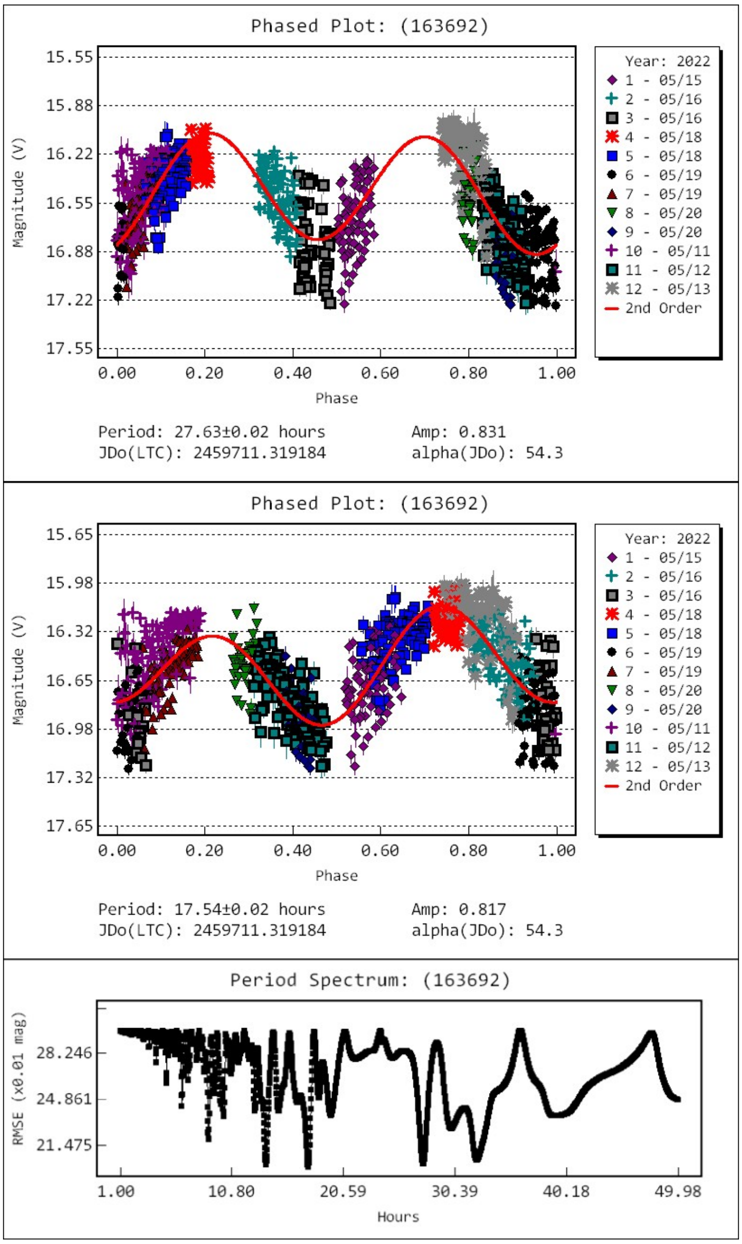

Fig. 5 – Lightcurves and periodogram for (163692) 2003 CY18.

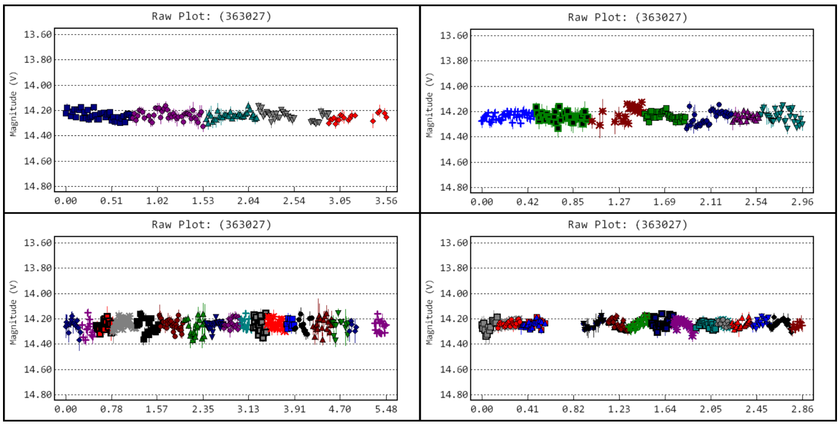

Fig. 6 – Raw lightcurves for (363027) 1998 ST27.

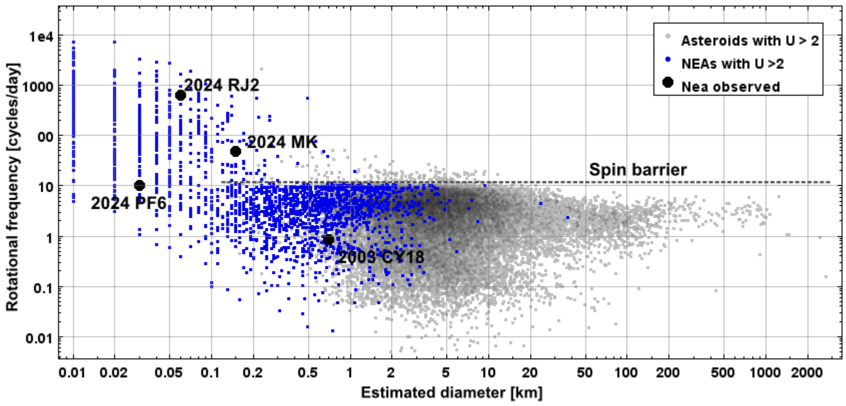

Fig. 7 – Position of the four observed asteroids on the rotational frequency vs. diameter diagram for NEAs. Data plotted from LCDB – Oct 2023 version.

metric data spanning 26.06 years: $A_2 = 1.65 \times 10^{-14} \pm 3.4^{-16} au/d^2$. The SNR of this detection, defined as $|A_2|/\sigma(A_2)$ (Farnocchia *et al.*, 2013), is of 48.5 indicating a robust detection of this effect in astrometric data. This result is similar with the one computed by JPL: $1.63^{-14} \pm 3.3^{-16} au/D^2$ (https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=1998ST27). The corresponding semimajor axis drift rate of this prograde rotator is: $da/dt = 10.8 \times 10^{-4} au/My$.

For 2003 CY18 the detection was marginal with $A_2 = -4.34 \times 10^{-14} \pm 2.6 \times 10^{-16} au/d^2$. Although this value seems to indicate a retrograde rotator, more precise radar and optical observations are required to definitely confirm the Yarkovsky signal for this object.

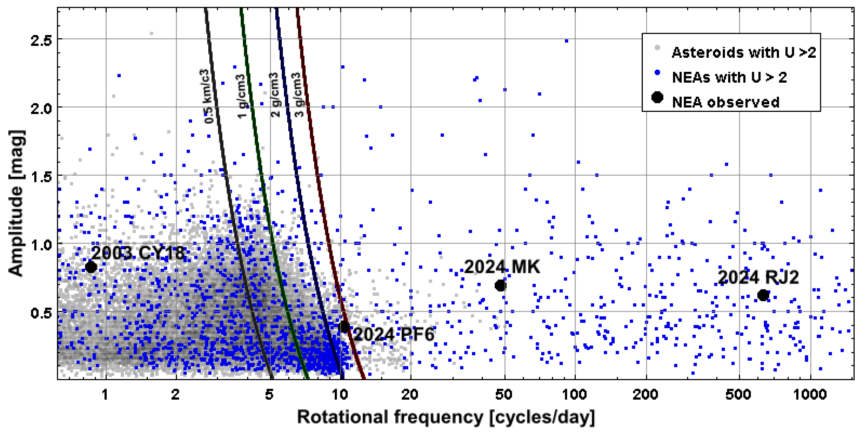

Fig. 8 – Amplitude of brightness variation vs. the rotation frequency of asteroids. Superimposed are the rotational limits (break-up limit) for asteroids with different densities. From this plot we can estimate, within error limits of our data, a maximum density for the observed asteroids. Data plotted from LCDB – Oct 2023 version.

The orbit computation procedure for 2024 MK reveals no Yarkovsky signature in the astrometric data.

We note that for both fast (2024 MK) and slow (2003 CY18) rotators the Yarkovsky effect was not identified. This is an expected result since in this extreme cases the body will reach an equlibrium temperature for fast rotators or the transverse component of the accelerations will be missing if the asteroid is a slow rotator.

The inferred value of A_2 for 1998 ST27 can be further used to estimate its bulk density.

4. CONCLUSION

We determined the values of the rotational period and amplitude of four Near Earth Asteroids and a higher limit for the rotational parameters for one Near Earth Asteroids, from observations made at Berthelot and Bucharest Observatories. For asteroids 2024 RJ2, 2024 MK, and 2024 PF6, our results are the first published (at the time of the article).

We found that 2024 RJ2 is a very fast rotator ($P = 2.2$ min) and that 2024 MK exhibits two rotation periods, being in non-principal axis (NPA) rotational motion. For the asteroid (163692) 2003 CY18 we partially confirm the result of Warner and Stephens (2020), while for (363027) 1998 ST2 we provide only an upper limit for the amplitude of variation. We also determined that 2024 MK and 2024 RJ2 could be monolithic bodies. For asteroid 1998 ST27 we detected a clear Yarkovsky signal in the astrometric data, while for 2003 CY18 the detection was marginal.

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Received on 9 December 2024