The Mission Accessible Near-Earth Objects Survey: Four Years of Photometry

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The Mission Accessible Near-Earth Objects Survey: Four Years of Photometry

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Abstract

Over 4.5 years, the Mission Accessible Near-Earth Object Survey assembled 228 near-Earth object (NEO) light curves. We report rotational light curves for 82 NEOs, constraints on amplitudes and periods for 21 NEOs, light curves with no detected variability within the image signal-to-noise and length of our observing block for 30 NEOs, and 10 tumblers. We uncovered two ultra-rapid rotators with periods below 20 s,—2016 MA with a potential rotational periodicity of 18.4 s, and 2017 GQ18 rotating in 11.9 s—and estimated the fraction of fast/ultra-rapid rotators undetected in our project plus the percentage of NEOs with a moderate/long periodicity undetectable during our typical observing blocks. We summarize the findings of a simple model of synthetic NEOs to infer the object’s morphology distribution using the measured distribution of light curve amplitudes. This model suggests that a uniform distribution of axis ratio can reproduce the observed sample. This suggests that the quantity of spherical NEOs (e.g., Bennu) is almost equivalent to the quantity of highly elongated objects (e.g., Itokawa), a result that can be directly tested thanks to shape models from Doppler delay radar imaging analysis. Finally, we fully characterized two NEOs—2013 YS2 and 2014 FA7—as appropriate targets for a potential robotic/human mission due to their moderate spin periods and low Δν.

Key words: minor planets, asteroids: general

Supporting material: figure sets, machine-readable table


Our MANOS project started about 4.5 years ago and aspires to characterize mission accessible near-Earth objects (NEOs). Our project is designed to fully characterize NEOs, providing rotational light curves, visible and/or near-infrared reflectance spectra and astrometry. Such an exhaustive study will give us the opportunity to derive general properties regarding compositions, and rotational characteristics. Because existing physical characterization surveys have primarily centered on the largest NEOs with sizes above 1 km, MANOS mainly targets sub-km NEOs (Benner et al. 2015; Li et al. 2015; Reddy et al. 2015; Thirouin et al. 2016).

Our project is split into two main parts: (i) spectroscopy to provide surface composition, spectral type, taxonomic albedo and infer the object’s size; and (ii) photometry to provide rotational properties and astrometry. Below, we center our attention on the rotational characteristics of the MANOS NEOs extracted from the photometry.

Here, we present new data combined with results from Thirouin et al. (2016). Thanks to this homogeneous sample of 228 NEOs, we can perform statistical studies and understand the rotational characteristics of the small NEOs in comparison to the larger NEOs. In Sections 2-4, we briefly present our survey strategy and data analysis, in addition to presenting our light curves. Sections 5 and 6 respectively feature our results derived from the light curves and their implications. Section 7 details our simple model for creating three synthetic populations of light curves assuming different axis ratio distributions for comparison with the literature and our observations. The last section summarizes our conclusions.

2. MANOS: Observing Plan, Facilities, Data Analysis

In approximately 4.5 years, MANOS observed 308 NEOs for light curves (86 objects in Thirouin et al. 2016; 142 here, and the remainder will be reported in a future work). Figure 1 summarizes the objects observed by MANOS with NEOs from the LCDB (Warner et al. 2009). The LCDB contains 1359 entries for NEOs, and 1147 have a rotation estimate objects with a constraint for the period are not considered). The LCDB distribution peaks at pH ~ 17 mag (i.e., NEO with a diameter of D ~ 1 km for a geometric albedo of 20%, Pravec & Harris 2007), whereas for the MANOS sample the peak is at pH ~ 24 mag (i.e., D ~ 45 m).

MANOS employs a set of 1–4 m telescopes for photometric purposes: the 1.3 m Small and Moderate Aperture Research Telescope System (SMARTS) telescope at CTIO, the 2.1 m and the 4 m Mayall telescopes at Kitt Peak Observatory, the 4.1 m Southern Astrophysical Research (SOAR) telescope, and the Lowell’s Observatory 4.3 m Discovery Channel Telescope (DCT). A complete description of these facilities, the instruments used, and filters, is available in Thirouin et al. (2016). In 2016 January, Mosaic-1.1 was replaced by Mosaic-3 at the Mayall telescope. This new instrument is also a wide-field

9 Light-curve database (LCDB) from 2017 November.
3. MANOS: Photometry Summary

For this work, we classified the light curves in four main categories: (i) full light curve with a minimum of one entire rotation or a large portion of the light curve to estimate a periodicity, (ii) partial light curve showing a decrease or increase of the visual magnitude, but with not enough data for a period estimate, (iii) flat light curve with no obvious increase/decrease in variability and no period detected, and (iv) potential tumblers with or without the primary period (or shortest period, Pravec et al. 2005). We have full light curves for 82 NEOs (11\% of our data set), lower limits for periodicity and amplitude for 21 NEOs (15\%), flat light curves for 30 NEOs (21\%), and 10 NEOs are potential tumblers (7\%) (see Figure 2). We present two light curves (one flat and one full) for 2014 WU200. This case will be discussed below.

MANOS found the fastest known rotator so far, 2017 QG18 with a rotation of 11.9 s. This object was imaged at DCT in 2017 August, and the light curve has a variability of about 0.21 mag. The typical photometry error bar is 0.05 mag. We discovered the potential ultra-rapid rotator: 2016 MA. MANOS observed this object in 2016 June, and measured a short period of 18.4 s. The typical photometry error bar is 0.05 mag. The light curve displays low variability with a full amplitude of 0.12 mag. Unfortunately, the confidence level of this periodicity is low (i.e., <99.9\% confidence level stated for a period estimate) and more data are required to infer if 2016 MA is an ultra-rapid rotator or not. In summary, MANOS discovered four ultra-rapid rotators with periodicities below 20 s: 2014 RC, 2015 SV6, 2016 MA, and 2017 QG18 (Thirouin et al. 2016, and this work).

3.1. Asymmetric/Symmetric and Complex Light Curves

Only three NEOs display a symmetric light curve, 2014 UD27, 2014 WF201, and 2017 LD, whereas 66 have a bimodal light curve with two different peaks (i.e., asymmetric curve). The majority of the MANOS NEOs have an asymmetry <0.2 mag, but sometimes, the difference is higher: 2013 SR and 2015 KQ126 with an asymmetry of 0.2 mag, 2014 FF with 0.3 mag, 2014 HN178 with 0.4 mag, and 2014 KH39 with 0.7 mag.

Thirteen objects have complex light curves that cannot be fit with only two harmonics: 2014 HS18, 2014 HW, 2016 BF1, 2016 DK, 2016 ES1, 2017 EK, 2017 EZ2, 2017 HV3, 2017 JM2, 2017 KZ27, 2017 LE, 2017 MO8, and 2017 QX1. The reasons for this morphology are as follows: (i) complex shape (NEOs far from spherical/ellipsoidal shapes), and/or (ii) albedo contrast, and/or (iii) satellite. More observations in different geometries will be useful for shape modeling and to probe for a companion. Unfortunately, most of them will not be brighter than 21 mag in the upcoming decade.

3.2. Partial Light Curves

Twenty-one objects display an increase/decrease in magnitude (red arrows Figure 2). We did not calculate a secure periodicity because our observations spanned less than 50\% of the NEO’s rotation. For example, 2016 JD18 was imaged with Lowell’s DCT for a span of 0.5 hr. The partial light curve presents a large amplitude of 1.2 mag and a feature possibly suggesting a complex shape.

10 Light curves and photometry files can be found at manos.lowell.edu.
11 We have 2 light curves for 2014 WU200. Only the full light curve is considered for these estimates.

12 Tumblers are not considered in this subsection.
3.3. Tumblers

We found ten potential tumblers: 2013 YG, 2014 DJ80, 2015 CG, 2015 HB177, 2015 LJ, 2016 FA, 2016 RD34, 2017 EE3, 2017 HU49, and 2017 QW1. We derive their main periodicities and report them in Table 1. For three of them, we are not capable of deducing the main period. In all cases, our data were insufficient to derive the second period with the Pravec et al. (2005) technique.

3.4. Flat Light Curves

Thirty objects have no detected periodicity in the measured photometry. These flat light curves can be due to: (i) a long/very long periodicity that was not detected over our observing window, (ii) a rapid rotation consistent with the exposing time, (iii) a (nearly) pole-on configuration, or (iv) a NEO with a spheroidal shape. Below, we discuss these four scenarios by assuming that all small NEOs are fast rotators and large NEOs are slow rotators. Such an assumption is based on the well-known rotational period-size relation (Figure 2), but it is important to emphasize that our assumption may not be right for all objects, as some small objects have been found to be slow rotators (Warner et al. 2009). Thus, MANOS can be identifying slow or fast rotators in the small size range.

4. Flat Light Curves: Four Scenarios

4.1. Slow Rotators

As we only dedicate a short observing block per object (typically ~2–3 hr, or shorter in case of weather or technical issues), we are biased against long rotational periods (typically, longer than 5–6 hr). Five objects from this work and Thirouin et al. (2016) were observed by other teams that derived the following rotation periods: 1994 CJ1 (~30 hr, Warner 2015b), 2008 TZ3 (44.2 hr, Warner et al. 2009), 2013 YZ57 (8.87 hr, Warner 2014), 2014 SM143 (2.9 hr, Warner 2015c), and 2015 LK24 (18.55 hr, Warner 2015a). For 2014 SM143, the Warner (2015c) observations and ours are separated by about 8–10 days. In both cases, data were obtained at high phase angle (>50°). We observed 2014 SM143 over ~2.5 hr with a typical photometric error bar of 0.1 mag and should have detected such a period, assuming that the period derived by Warner (2015c) is correct. However, Warner (2015c) presented a noisy photometry and their period spectrum showed several solutions that were marginally significant. Therefore, the authors are not confident about their results, and the reported period could be wrong. Our results for 2014 SM143 are available in Thirouin et al. (2016).

We expect “large” objects with $D > 100$ m (i.e., $H > 22.4$ mag) to have a slow rotation (Figure 2). Therefore, 2004 BZ74a, 2005 RO33, 2007 CN26, 2008 HB38, 2010 CF19, 2011 ST323, 2011 WU95, 2012 ER14, 2012 XQ93, 2014 CP13, 2014 OA2, and 2014 YD42 are probably slow rotators with periods undetected over our short sampling. 2013 UE3, and 2016 AU65 ($H = 22.7$ mag, and 22.9 mag, respectively) are likely slow rotators too (Figure 2). There are no other published data on these objects for comparison to our results. The length of our observing blocks is the lower limit for their periods.

In conclusion, 19 large objects ($D \gtrsim 100$ m) in the full MANOS sample are potential slow rotators (i.e., ~8% of the full sample reported in Thirouin et al. (2016) and here). Thus, we estimate that at least 43% of our flat light curves from this work and our previous paper are caused by slow rotation undetectable over our typical observing blocks. It is crucial to mention that for this estimate, we consider that all large objects are slow rotators, which may not be the case for all of them.

4.2. Pole-on Orientation

Pole orientations are known for a handful of large NEOs with diameters of several km (e.g., La Spina et al. 2004; Benner et al. 2015; Vokrouhlický et al. 2015). Shape modeling with radar observations and/or light curves obtained at different epochs are required to estimate the pole orientation. MANOS targets typically fade in a matter of hours or days, and their next optical window is often decades away, so light curves at different epochs/observing geometries are generally not feasible. For fast and small rotators, radar techniques cannot construct the object’s shape, and thus no pole orientation is derived.

The pole orientation distribution of large objects in the main belt of asteroids (MBAs) is isotropic, whereas small MBAs and NEOs ($D < 30$ km) have preferentially retrograde/prograde rotation (La Spina et al. 2004; Hanus et al. 2013; Vokrouhlický et al. 2015). Vokrouhlický et al. (2015) reported 38 pole solutions with an excess of retrograde-rotating NEOs, and noticed a clear deficit of small MBAs and NEOs with a pole orientation of $0°$. The MANOS set is mostly composed of NEOs in the sub-100 m range, and unfortunately, there is no comprehensive information about pole orientation for this size range. However, if the sub-100 m NEOs follow the same trend as small main-belt asteroids and large NEOs, then we expect an excess of small bodies with a pole orientation of $\sim \pm 90°$.

If the rotation axis of an elongated NEO and the sight line are (nearly) aligned, the brightness variation due to its rotation will be undetectable. Depending on the aspect angle ($θ$), the light-curve amplitude of an elongated object ($a > b > c$) is:

$$
\Delta m = 2.5 \log \left( \frac{\bar{a} \cos^2 \theta + \bar{a}^2 \bar{c}^2 \sin^2 \theta}{\bar{a}^2 \cos^2 \theta + \bar{c}^2 \sin^2 \theta} \right),
$$

where $\bar{a} = a/b$, $\bar{b} = 1$, and $\bar{c} = c/b$. The likelihood of observing an object pole-on is $P = 1 - \cos \theta$ (Lacerda & Luu 2003). As an example, the probability of viewing a small body with a pole-on orientation $\pm 5°$ is $<1%$. Therefore, we estimate that only a few if any of our flat light curves are due to a pole-on orientation.

4.3. Spherical Objects

Using the previous equation, the largest amplitude will be at $θ = 90°$, and the smallest will be at $θ = 0°$ and $180°$. At $θ = 90°$, $\Delta m = 2.5 \log(\bar{a})$. Therefore, the brightness variability of an almost spherical object will be flat. As noted, shape modeling using radar observations and/or light curves at different epochs are required to derive the object’s shape. However, there are very few shape models available for sub-100 m NEO (Benner et al. 2015).

Several NEOs with $D > 200$ m have an oblate shape with a ridge at the equator or a diamond shape, and they are predicted to be relatively common (Benner et al. 2015). Objects like Bennu, 2008 EV5, 2004 DC, 1999 KW4, and 1994 CC have an oblate shape based on radar observations, and a low to moderate light curve amplitude with periods longer than 2 hr (Ostro et al. 2006; Pravec et al. 2006; Taylor 2009; Warner et al. 2009; Brozović et al. 2011; Busch et al. 2011; Nolan et al. 2013;
### Observing Log and Results

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### Parameters

- \(r_\text{a} \): semimajor axis (au)
- \(\Delta \): semimiss distance (au)
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- Tel: telescope
- \(\mathcal{T} \): observation time (minutes)
- \(t_{\text{exp}} \): exposure time (s)
- Rot. P.: rotation period (hr)
- \(\Delta m \): magnitude change (mag)
- \(\varphi_0 \): phase at epoch (2450000+)
- H: opposition distance (m)
- D: opposition (m)
- \(\mathbf{v}_\text{SH} \): heliocentric velocity (km s\(^{-1}\))
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**Flags**
- light curve
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Notes.

- UT-date, distance Sun-object ($r_h$), and distance Earth object ($\Delta$), and phase angle ($\alpha$) are summarized. The filter (details in Thirouin et al. 2016), telescope (Tel) and number of images (Nbim), rotational period (Rot. P. in hour), relative amplitude ($\Delta m$), and the Julian Date ($\phi_0$) for the zero phase are presented. No light-time correction is applied. Absolute magnitude ($H$), and an estimate of the NEO diameter ($D$) with 20% as albedo are also reported. Exposure time ($t_{exp}$), and duration of the observing block ($\Delta T$) for each NEO are indicated.
- Two other light curves have been published for this object by Warner (2015c), suggesting a rotational period of 31 hr and by Kikwaya Eluo (2018) with a periodicity of 1 hr. For the purposes of our work, we use the MANOS result reported here.
- Two light curves are reported for this object (Section 4).

(This table is available in machine-readable form.)
Benner et al. 2015). Assuming that small NEOs are following the same tendency as NEOs with $D > 200$ m, some MANOS NEOs are potentially oblate. Oblate objects appear to have long rotational periods that are consistent with/longer than the length of our runs. Therefore, some of our flat light curves are potentially caused by oblate objects. Unfortunately, as there is no estimate for the quantity of oblate rotators (independent of size) or if small NEOs have the tendency to be oblate, we cannot propose a clear percentage.

### 4.4. Fast Rotators

The periodicities of small NEOs ($D < 100$ m) may be undetected as a result of “long” exposure times. For example, we report two light curves for 2014 WU$_{200}$. One of the light curves is flat, but the second displays periodic photometric variations. The first light curve was obtained on 2014 November 26th at DCT. The visual magnitude of 2014 WU$_{200}$ was 20.7 mag (MPC estimate). Due to the faintness and bad atmospheric conditions, we selected an exposing time of 45–55 s (+read-out of 13 s). The typical photometry error bar was 0.03 mag for the DCT data. With the Mayall Telescope we reobserved this object few days later when the magnitude was 20.1 mag (MPC estimate). In this case, we employed 10 s as the exposure time (+11 s of read-out time), and we favored a rotation of $\sim$64 s. The typical photometry error bar was 0.05 mag for the Mayall data. Therefore, the exposing time used at DCT was too long to derive such a short period.

Some of our objects with flat light curves were imaged with exposures between 30 and 300 s. These values were selected for a decent signal-to-noise ratio, but these times may not have been optimal to sample the light curve and so no periodic photometric variations were detected. We estimate that 23 MANOS NEOs are maybe fast to ultra-rapid rotators whose rotations were undetected due to a “long” exposing time and/or the bad weather conditions. Small NEOs are commonly rotating fast (Figure 2), and if so, 52% of our flat light curves from this work and Thirouin et al. (2016) are potentially due to small ultra-rapid/fast rotators.

For fast/ultra-rapid NEOs rotating over a few seconds or few minutes, the exposure time is important. Following Pravec et al. (2000), the optimum exposure time ($T^\text{opt}$) to detect a light curve with two harmonics is

$$T^\text{opt}_{\text{exp}} = 0.185 \times P,$$

with $P$ as the object’s periodicity (Section 2 of Pravec et al. 2000). This relation is based on theory and does not reflect a specific observing strategy. Because we know the exposing time during our observations, we can figure out the detectable rotational period. For example, with $T_{\text{exp}} = 11$ s, we will perfectly sample the light curve of a small body rotating in 1 minute or more. In this case, an object rotating in $\leq 1$ minute will have a flat light curve and thus its rotation will be undetectable.

In Figure 3, the continuous line is for Equation (2) for a perfectly sampled two harmonic light curve. The data points are MANOS NEOs imaged with our 4 m facilities. Objects below the continuous line have oversampled light curves, whereas above this line the light curves are undersampled. The dashed line in Figure 3 represents an empirical upper limit to the period-exposure time relationship using the MANOS data set and can be articulated as

$$T^\text{MANOS}_{\text{exp}} = 0.48 \times P.$$  (3)

This relation would converge to Nyquist sampling theory in a regime of infinite signal-to-noise ratio. For the smallest objects, and thus potentially fast to ultra-rapid rotators, using Equation (3) we can identify the rotational period to which we were sensitive based on object-specific exposure time. Using Equations (2) and (3), we have two lower limits for the potential rotational periods. Therefore, if these objects have a rotational period between these two estimates, we should have detected it. In conclusion, the rotational period is likely shorter than the estimate and thus we undetected it in our observing block (assuming that the objects have a two-harmonics light curve). But it is also important to emphasize that some small objects (sub-100 m objects), even if they are expected to rotate fast, might be slow rotators (Figure 2).

### 5. Physical Constraints

A strengthless rubble-pile will not be able to rotate faster than about 2.2 hr without breaking up (Pravec et al. 2002). But most small NEOs have rotational periods of a few seconds or minutes. Therefore, an explanation for these rapid rotations is that NEOs are bound with tensile strength and/or cohesion instead of just gravity. Using Holsapple (2004, 2007), we calculated the maximum spin limits assuming different densities and tensile strength coefficients for the NEO population. Following Richardson et al. (2005), we considered a friction angle of 40°, and moderately elongated ellipsoids ($\epsilon/a = b/a = 0.7$). We used two values for the density; 2 (Iokawa (Fujiiwara et al. 2006)) and 5 g cm$^{-3}$ (density of a stony-iron object (Carry 2012)), and two tensile strength coefficients, 10$^7$, and 10$^8$ N m$^{-3/2}$ (with a range of tensile strengths for Almahata Sitta; Kwiatkowski et al. 2010). Five MANOS targets require a tensile strength coefficient between $10^5$–$10^6$ N m$^{-3/2}$: 2014 FR$_{52}$, 2014 PR$_{52}$, 2015 RF$_{36}$, 2016 AD$_{166}$, and 2016 AO$_{131}$.
The light-curve amplitudes ($\Delta m(\alpha)$) in Table 1 were obtained at a phase angle $\alpha$. At $\alpha = 0^\circ$, the amplitude is

$$\Delta m(\alpha = 0^\circ) = \frac{\Delta m(\alpha)}{1 + s\alpha},$$

(4)

with $s = 0.03$ mag deg$^{-1}$ (Zappala et al. 1990). In the MANOS sample, only 12 objects (10% of our sample) have a $\Delta m$ ($\alpha = 0^\circ$) $\geq 0.5$ mag, and one object has a $\Delta m$ ($\alpha = 0^\circ$) $\geq 1$ mag. In the LCDB, there are 309 NEOs with an absolute magnitude $H \geq 20$ mag, that are observed at a phase angle $\alpha \leq 100^\circ$; 47 of them have a $\Delta m$ ($\alpha = 0^\circ$) $\geq 0.5$ mag (15% of the LCDB), and 6 have a $\Delta m$ ($\alpha = 0^\circ$) $\geq 1$ mag (2%). Therefore, the relative abundance of high amplitude light curves in these two data sets is consistent.

6. Potential Mission Targets

One of our goals is to find favorable target(s) for a future mission to a NEO, and thus mission accessibility is one of our selection criteria (Abell et al. 2009; Hestroffer et al. 2017; Bambach et al. 2018). For this purpose, we estimate the velocity change for a Hohmann transfer orbit also known as $\Delta v$. A rough guess of the $\Delta v$ is estimated with the Shoemaker & Helin (1978) protocol ($\Delta v^{NHATS}$). In order to obtain an accurate estimate, one can use the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) orbital integration, $\Delta v^{NHATS}$ is NHATS uses specific constraints to compute the $\Delta v^{NHATS}$ (i) launch before 2040, (ii) total mission duration $\leq 450$ days, and (iii) number of days spent at the object $\geq 8$ days. The NHATS limit is $\Delta v^{NHATS}$ of 12 km s$^{-1}$. Several of our targets do not follow these criteria, so no $\Delta v^{NHATS}$ are available for them (Table 1).

According to NHATS, 78 MANOS NEOs are accessible with a spacecraft (Table 2, and Table 2 in Thirouin et al. 2016). For diverse reasons, Abell et al. (2009) found that the best target for a mission should have a moderate to slow rotation ($P > 1$ hr). Only 9 MANOS NEOs have such a long rotation, have a $\Delta v^{NHATS} \leq 12$ km s$^{-1}$; and have been observed for spectroscopy (Table 2, and Table 2 in Thirouin et al. 2016). We will present spectral results for these objects in future publication(s).

Finally, we note that several non-fully characterized MANOS NEOs have a new optical window in the upcoming years or decades. For example, the low $\Delta v^{NHATS}$ and slow rotator 2013 Xx8 (spectral type unknown) will have a new optical window in 04/2019, thus we will have an opportunity to fully characterize this potential target.

7. MANOS+LCDB Versus Synthetic Population

In this section, we aim to compare our results to a synthetic population of NEOs to identify biases regarding our measured amplitude distribution and to constrain the distribution of morphologies in the NEO population. In a first step, we create 10,000 synthetic objects and calculate their light-curve amplitude versus phase angle. In a second step, we “observationally sample” this synthetic population based on prescribed phase angles, in order to compare our synthetic population with the MANOS+LCDB data set.

Step 1: Assuming that NEOs are prolate ellipsoids (with $b = c$) at a phase angle of $0^\circ$, the amplitude varies as

$$\Delta m(\theta) = 1.25 \times \log \left[ \frac{1}{\cos^2 \theta + (b/a)^2 \sin^2 \theta} \right],$$

(5)

where $\theta$ is the aspect angle, and $b/a$ is the elongation of the object (Michalowski & Velichko 1990). The aspect angle is

$$\cos \theta = -\sin \beta_p \sin \beta_p - \cos \beta_p \cos \beta_p \cos (\lambda_g - \lambda_p),$$

(6)

where $\beta_p$ and $\lambda_p$ are the object’s north pole ecliptic latitude and longitude, and $\lambda_g$ and $\beta_g$ are the object geocentric ecliptic coordinates (Michalowski & Velichko 1990). We use Equation (5) to generate the light-curve amplitude of 10,000 synthetic objects. The only two free parameters in this equation are the axis ratio $b/a$ and the viewing angle $\theta$. In theory, the axis ratio $b/a$ varies from 0 to 1. However, for objects visited

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14 The observing circumstances or light curve amplitude are not reported for some LCDB objects, and thus they are not considered here. Only NEOs with a $H \geq 20$ mag are considered because MANOS focuses on small objects. We select objects observed at a phase angle lower than 100$^\circ$ because MANOS is observing in that range.

15 http://neo.jpl.nasa.gov/nhats/
Table 2

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Note.

* MANOS obtained spectra and light curves for two good spacecraft targets (italic/bold), but we also summarize all NEOs with a rotational period longer than 1 hr. For completeness purposes, $\Delta_{SH}$ and $\Delta_{NHATS}$ following the Shoemaker & Helin (1978) protocol and the NHATS parameters are summarized. The start of the next opportunity to observe these objects according to NHATS is also shown (https://cneos.jpl.nasa.gov/nhats/).

by spacecraft, Eros\(^{16}\) is the most elongated with a ratio $b/a = 0.32$ (Veverka et al. 2000). Thus, we limit the axis ratio $b/a$ between 0.32 and 1 spherical object. We considered three possible axis distributions for our synthetic population: (i) a uniform distribution of $b/a$, (ii) one distribution with an excess of spheroidal objects, and (iii) one with an excess of elongated objects (Figure 5, upper panel).

The second parameter is the aspect angle $\theta$ ranging from from 0° to 90° (absolute value). La Spina et al. (2004) and Vokrouhlický et al. (2015) noticed an excess of retrograde-rotating NEOs (based on a limited sample), which would imply that the observed distribution of pole orientations is not uniform. We updated the distribution of poles reported in Vokrouhlický et al. (2015) with the newest results from the LCDB (multiple systems have been excluded from the distribution, as we do not expect any small NEO as binary/multiple, Margot et al. 2002). With the newest results, the pole distribution is still consistent with the Vokrouhlický et al. (2015) result. Using our updated pole distribution, we created a non-uniform distribution of pole orientation and thus a distribution of $(\lambda_p; \beta_p)$. Even though most of the objects with a known pole orientation are large objects, and we assume that the pole orientation of the small objects is similar to that of large objects, this assumption might be wrong and will need to be tested once more pole orientations of small objects are known. The typical uncertainty on pole orientation is about $\pm 10^\circ$ based on radar and light-curve inversion results, so we estimated the number of objects within a grid of $10^\circ \times 10^\circ$. We use the number density of objects in this grid of pole coordinates to randomly assign a pole orientation to each of our 10,000 synthetic objects.

Equation (6) also depends on the geocentric ecliptic coordinates $(\lambda_p; \beta_p)$. For the MANOS sample, we use the zero phase of our light curve to estimate the $(\lambda_p; \beta_p)$ of our objects. In order to present the most accurate sample, we also incorporated the LCDB objects with $H > 20$ mag. Unfortunately, authors generally did not report the zero phase timing of their light curves, so we used approximate coordinates for those objects based on the observing nights reported in the literature. Once $(\lambda_p; \beta_p)$ were estimated for the MANOS+LCDB sample, we created a grid of geocentric ecliptic coordinates of $10^\circ \times 10^\circ$. Such a grid allowed us to take into account the approximate coordinates of the LCDB objects.\(^{17}\) Therefore, we created a distribution of $(\lambda_p; \beta_p)$ based on the observations from the MANOS+LCDB sample (Figure 4, upper plot). Using this and the distribution of $(\lambda_p; \beta_p)$, we calculated the distribution of aspect angles (Equation (6)), which were then used as input to Equation (5) to calculate a synthetic population of light-curve amplitudes at zero phase.

Step 2. As the aspect angles of our observed sample are unknown, we cannot directly compare our data set and the synthetic population. However, we can effectively observe our synthetic objects by assigning a phase angle based on the observed distribution of phase angles for MANOS+LCDB objects. By merging Equations (4) and (5), we estimate the light-curve amplitude of our synthetic population at these

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\(^{16}\) Only objects visited by spacecraft were taken into account because of the direct estimate of their size/axis ratio.

\(^{17}\) For observations during close approach, some objects may move more than $10^\circ \times 10^\circ$ and thus are not in the right grid; however, this applies to a small number of objects and will not change the main conclusions of our simulations.
the number of objects per bin. In Section 7 the other plots report the light-curve amplitude non-corrected from phase angle of the two synthetic distributions, as well as the MANOS+LCDB sample. The lower panel focuses on objects with an amplitude between 0.1 and 1.5 mag. The error bars are $\sqrt{1/N}$, with $N$ being the number of objects per bin.

prescribed phase angles. In Figure 4, we plot the MANOS sample and the LCDB objects with a $H > 20$ mag and a phase angle lower than 100°. We limit this analysis to small objects observed at a phase angle between 0° and 100° in order to mimic the MANOS sample. Based on Figure 4 (lower plot), it is obvious that the MANOS and LCDB observations are not uniform with phase angle. In fact, both data sets have an excess of objects observed at low/moderate phase angle (up to $\sim 40^\circ$), and only an handful of objects are observed at high phase angle ($\alpha > 80^\circ$). Drawing from the distribution of MANOS+LCDB objects, we create a non-uniform distribution of phase angles for our synthetic population (Figure 4, lower panel), and then calculate the amplitude of our 10,000 synthetic objects.

In Figure 5 (lower panel), we plot the normalized histogram of light-curve amplitude for the synthetic population and the MANOS+LCDB samples. The error bars are $\sqrt{1/N}$, with $N$ being the number of objects per bin. We limit our distribution to light-curve amplitudes up to 1.5 mag, as only a handful of objects with higher light-curve amplitudes are reported. Generally, objects with low light-curve amplitude are difficult to obtain, as they require a large amount of observing time under good weather conditions. In addition, observers have the tendency to not report or publish flat light curves. Therefore, there is a clear bias in the LCDB regarding these low-amplitude objects, thus we do not take into account objects with a light-curve amplitude $<0.1$ mag.

In Figure 5 (lower panel), we plot our three synthetic populations (uniform distribution of $b/a$, an excess of spherical objects and an excess of elongated objects) for amplitudes between 0.1 and 1.5 mag. In order to compare the simulated population and the observed sample, we calculate the $\chi^2$ per degree of freedom:

$$\chi^2 = \frac{1}{\nu} \sum_{i} \left[ \frac{f(\Delta m_i) - \Delta m_i}{\sigma_i} \right]^2,$$

where $\nu$ is the degree of freedom, $\Delta m_i$ are the observed data, $f(\Delta m_i)$ are the simulated results, and $\sigma_i$ are the uncertainties (i is the index of the bin and $n$ is the bin number). Comparing the MANOS+LCDB data with the excess of elongated object distribution, we find a $\chi^2/\nu$ of 2.67. The MANOS+LCDB sample compared to the excess of spherical object distribution gives us a $\chi^2/\nu$ of 1.17, whereas compared to the uniform distribution the $\chi^2/\nu$ is 0.31. This suggests that a uniform distribution of $b/a$ best fits the observed sample. Our model assumes a basic uniform distribution of $b/a$ for prolate ellipsoids. Future improvements to this model could employ more realistic shapes based on radar observations and/or light-curve inversion.

8. Summary/Conclusions

We report full light curves for 57% of our sample (82 NEOs), and constraints for the amplitude and period are reported for 21 NEOs. Thirty NEOs do not exhibit any periodic variability in their light curves. We also report 10 potential tumblers.

MANOS found a potential new ultra-rapid rotator: 2016 MA. This object has a potential periodicity of 18.4 s. The confidence level of this periodicity is low and more data are required to confirm this result. Unfortunately, there is no optical window to re-observe this object until 2025, and even then it only reaches $V \sim 22.5$ mag. We also uncovered the fastest rotator to date, 2017 QG18, rotating in 11.9 s.

Several MANOS targets display a flat light curve. Because of the well-known relation between size and rotational period, we can infer that large objects ($D > 100$ m) are slow rotators and their rotational periods were undetected during the amount of observing time dedicated. Based on this size-dependent cut, we estimate that 43% of our flat light curves are slow rotators with a rotational period longer than our observing blocks. A flat light curve of a small NEO can be attributed to fast/ultra-rapid rotation which goes undetected because of the long exposing time used to retrieve a good signal-to-noise ratio. We suggest that 52% of our flat light curves are potential fast/ultra-rapid rotators. We use the size of the object as a main criteria for these findings. This is an acceptable approximation, but may not be true for all the objects.

We present a simple model to constrain the light-curve amplitude distribution within the NEO population. One of the main parameters of our model is the $b/a$ axis ratio of an object. We create several axis distributions, using a uniform distribution as well as an excess of spherical and elongated objects. Assuming that the pole orientation distribution reported in

![Figure 5. We consider two non-uniform distributions of $b/a$ (upper panel) with an excess of elongated objects or an excess of spheroidal objects. Following the procedure presented in Section 7 the other plots report the light-curve amplitude non-corrected from phase angle of the two synthetic distributions, as well as the MANOS+LCDB sample. The lower panel focuses on objects with an amplitude between 0.1 and 1.5 mag. The error bars are $\sqrt{1/N}$, with $N$ being the number of objects per bin.](image-url)
Vokrouhlický et al. (2015) is representative of the NEO population, we generate 10,000 synthetic ellipsoids. We inferred that an uniform distribution of $b/a$ best matches the observed sample. This suggests that the number of spherical NEOs is roughly equivalent to the number of highly elongated objects.

A total of 78 MANOS objects are mission accessible according to NHATS, which assumes a launch before 2040. However, considering only fully characterized objects, and NEOs rotating in more than 1 hr, our sample of viable mission targets is reduced to nine objects: 2002 DU$_3$, 2010 AF$_{30}$, 2013 NJ, 2013 YS$_2$, 2014 FA$_7$, 2014 FA$_{44}$, 2014 YD, 2015 FG$_{36}$, and 2015 OV. Two of these nine objects will be bright enough during their next observing windows for new and complementary observations: 2013 YS$_3$ will have a $V \sim 18$ mag in 2020 December–January, and the visual magnitude of 2002 DU$_3$ will be 20.6 mag in 2018 November.

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Appendix A

Examples of Lomb periodograms for an object reported in this work.

![Lomb periodogram of 1999 SH10](image)

**Figure 6.** Example Lomb periodogram of 1999 SH10. Lomb periodograms are plotted with several confidence levels (continuous line: 99.9%; dotted line: 99%; and dashed line: 90%).

(The complete figure set (86 images) is available.)
Appendix B

Examples of the light curves of objects reported in this work.

Figure 7. Example MANOS light curve results are plotted. Light curves and photometry files can be found at manos.lowell.edu. (The complete figure set (16 images) is available.)

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