Characterization of Near-Earth Asteroids Using KMTNET-SAAO

N. Erasmus1, M. Mommert2, D. E. Trilling1,2, A. A. Sickafouse1,3, C. van Gend1, and J. L. Hora4
1 South African Astronomical Observatory, Cape Town, 7925, South Africa; nerasmus@sao.ac.za
2 Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86001, USA
3 Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
4 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138-1516, USA

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Abstract

We present here VRI spectrophotometry of 39 near-Earth asteroids (NEAs) observed with the Sutherland, South Africa, node of the Korea Microlensing Telescope Network (KMTNet). Of the 39 NEAs, 19 were targeted, but because of KMTNet’s large 2° × 2° field of view, 20 serendipitous NEAs were also captured in the observing fields. Targeted observations were performed within 44 days (median: 16 days, min: 4 days) of each NEA’s discovery date. Our broadband spectrophotometry is reliable enough to distinguish among four asteroid taxonomies and we were able to confidently categorize 31 of the 39 observed targets as either an S-, C-, X-, or D-type asteroid by means of a Machine Learning algorithm approach. Our data suggest that the ratio between “stony” S-type NEAs and “not-stony” (C+X+D)-type NEAs, with H magnitudes between 15 and 25, is roughly 1:1. Additionally, we report ~1 hr light curve data for each NEA, and of the 39 targets, we were able to resolve the complete rotation period and amplitude for six targets and report lower limits for the remaining targets.

Key words: minor planets, asteroids: individual (near-Earth objects) – surveys – techniques: photometric

Supporting material: data behind figure, figure sets, machine-readable table

1. Introduction

Near-Earth Asteroids (NEAs) are a group of asteroids that have orbits that bring them close to the Earth’s orbit. The majority are either Apollos or Amors that have Earth-crossing orbits, and these pose a direct threat to Earth as they potentially have impacting orbits, the most significant recent example being the Chelyabinsk airburst in 2013 speculated to be a fragment of the NEA 1999 NC43 (Borovička et al. 2013; Brown et al. 2013). While more recent work has shown that this link between Chelyabinsk and 1999 NC43 is tenuous at best (Reddy et al. 2015), impacts are still inevitable in the future and mitigation strategies is a subject undergoing intense study (Sanchez et al. 2009). On the other hand, the close proximity of NEAs to Earth has its benefits. Being nearby on an astronomical scale makes them convenient small solar system objects to characterize with Earth-bound measurements (see Figure 1 for an example image of our Korea Microlensing Telescope Network (KMTNet) observations). Coming close to Earth also makes them attractive objects to visit and investigate with spacecraft. This is evident with the numerous ongoing and proposed space exploration missions from the scientific community, like JAXA’s Hayabusa (Yano et al. 2006) and Hayabusa2 (Tsuda et al. 2013) missions, and NASA’s OSIRIS-REx (Lauretta et al. 2017) and DART (Cheng et al. 2016) missions. There is also an increasing interest in space mining endeavors from the technology and industrial community (Elvis 2012). Determining the physical properties and composition of NEAs is critical to all of the above.

Other than planetary defense, space exploration, and more recently space mining, NEAs are of interest from a more fundamental scientific research perspective as well. The source of the NEA population has been a postulated topic for decades. Currently, the most widely accepted model postulates that the NEA population is in steady state and is continuously being replenished by asteroids from the main asteroid belt through resonant motion with Jupiter and Saturn (Bottke et al. 2000; Granvik et al. 2017). However, these distribution models assume a uniform and size-independent compositional distribution, and therefore composition survey studies like this and others (e.g., Mommert et al. 2016) can help with further refinements of future NEA distribution models.

One of the most common methods to determine asteroid composition remotely is with spectroscopy. The reflected light spectrum of an asteroid can be compared to the reflectance spectra of known collected meteorite types, and in this way the composition of asteroids can be inferred. The most widely used spectral system is the Bus-DeMeo taxonomic scheme (DeMeo et al. 2009) consisting of 24 spectral types and sub-types that covers the wavelength range of 0.45–2.45 μm. Although there are many taxonomic classes, NEAs mainly fall into two groups: silicon-rich (“stony”) asteroids, which are classified as S-type asteroids, and those that are “not-stony”, which could be one of several classes, the most common being C-type (carbonaceous) asteroids, X-type (several different possible compositions) asteroids, and lastly D-type (even more primitive material) asteroids. These three classes all have featureless flat or reddish spectral slopes in the visible region. Figure 2 shows reflectance spectra for these four classes.

In some cases, it is adequate to sample the reflectance spectra at strategic wavelengths using broadband filters in order to constrain the taxonomic class. This technique is referred to as spectrophotometry and is the method used in this study. In spectrophotometry, broadband photometric filters are used. This has the benefit of being employable to investigate fainter asteroids. This significantly increases the observable population numbers, as the size distribution is heavily skewed toward smaller asteroids (Mainzer et al. 2011).
explained. In Section 3, the photometric results of the 39 NEAs observed are presented. Section 4 describes how the color, classification and light curve of each NEA was determined from the photometric data. Sections 5 and 6 conclude this study by discussing the analyzed data, comparing to other published work, and presenting our conclusions.

2. Observations and Data Reduction

Observations were made with the Sutherland, South Africa, node of the KMTNet (Kim et al. 2016). The telescope has a primary mirror of 1.6 m in diameter and is fitted with four 9k × 9k CCDs, mosaicking the 2° × 2° field of view. Each CCD covers 1° × 1° of sky with a plate-scale of 0.40 arcsec pixel⁻¹ (Figure 1). The vertical and horizontal gaps between the CCDs are 184″ and 373″, respectively. Johnson-Cousins B-, V-, R-, and I-filters are installed and only sidereal tracking is available. The minimum recommended exposure time for an efficient cyclical observation is 60 s due to the large readout time of ~75 s.

Observations were completed over 23 nights falling between 2016 October 25 and 2017 February 20, and newly discovered NEAs were specifically targeted for this study. On average, 1–2 new NEAs are discovered every night (Galache et al. 2015) and recorded in the Minor Planet Center’s (MPC) NEA database. On each observing night, the database was queried for any new discoveries observable from Sutherland, and the latest and most promising candidates were selected. This approach meant targeted observations were performed within 44 days (median: 16 days, min: 4 days) of each NEA’s discovery date.

Telescope pointing was offset to place the asteroid in the center of the top-right CCD in order to avoid the gaps between the CCDs. Observations were performed alternating between B-, R-, and I-filters in the sequence VRVI, repeating the sequence continuously for roughly one hour per target. NEAs typically move non-sidereally between 0.5 and 5 arcsec minute⁻¹ mostly dependent on how close they are to Earth. The target lists included only objects moving slower than 2 arcsec minute⁻¹ to prevent any significant streaking in the chosen 60 s exposure. This exposure time limited this study to asteroids with magnitudes $V \lesssim 21$ to achieve the desired SNR in a single exposure of at least 10.

All observed fields were scanned for serendipitously observed asteroids by calculating the ephemerides for all ~700,000 known asteroids in the MPC’s database at the respective mid-time of the observation. Ephemerides were calculated using PyEphem and any asteroid falling within the observed field’s coordinate perimeter was flagged. Flagged asteroids were queried on JPL’s Horizons interface using the Python module CALLHORIZONS and discarded if $V > 21$. The uncertainties in coordinates given by Horizons were also recorded. In total, 2650 serendipitous asteroids were captured and the majority were main belt asteroids, with only 20 NEAs having uncertainties in the coordinates of <10 arcsec.

Photometry and light curve extraction was achieved using PHOTOMETRYPIPELINE developed by Mommert (2017). The pipeline utilizes the widely used Source Extractor software for source identification and aperture photometry. SCAMP is used for image registration. Both image registration and photometric calibration are based on matching field stars with star catalogs from the Sloan Digital Sky Survey, the AAVSO Photometric All-Sky Survey, and GAIA.

3. Results

Figure 3 shows the spectrophotometric data for 2 of the 19 targeted NEAs and 2 of the 20 serendipitous NEAs (see the electronic edition of Figure 3 for all observed NEAs). The data
are the calibrated photometric results generated by the PHOTOMETRYPIPELINE from the V-, R-, and I-filter images. Adjusted R and I data are also shown (inter-spaced between V data), which results in a final light curve (bottom set of data in each plot). See Sections 4.1 and 4.3 for details regarding the process for adjusting the R and I data points. Photometric uncertainties account for instrumental uncertainties as well as statistical uncertainties when compared to the photometric catalog.

For a single exposure, an SNR of 30–40 was achieved for targets with $V \approx 18$ and around 10 for $V \approx 21$. The SNR in the R-band was slightly better and in the I-band slightly worse.

For each image, the PHOTOMETRYPIPELINE also outputs cropped thumbnail images centered around the predicted position of the target. The aperture size and aperture position are also indicated. These thumbnail images were manually inspected for all data points. Data points were manually deleted where in the corresponding image it was clear that the wrong

Figure 3. The spectrophotometric data for 2 of the 19 targeted NEAs ((a) and (b)) and 2 of the 20 serendipitous NEAs ((c) and (d)). The targets are (a) 2016 UU80, (b) 2017 AC5, (c) 1997 UF9, and (d) 1984 SS (MacCready). The data are the calibrated photometric results generated by the PHOTOMETRYPIPELINE developed by Mommert (2017). The V (green circles), the R (red squares), and the I (burgundy diamonds) filter data are shown. A final light curve (bottom set of data in each plot) is constructed by offsetting R and I data with a constant value (see Section 4.3). The adjusted data points are displayed as smaller, hollow symbols interspersed with the V data. The lower limit on the amplitude is calculated using the difference between magnitudes highlighted with the gray triangle symbols. The triangles are situated where the mean of two adjacent data points have the minimum/maximum magnitude. See the text for further description. See the electronic edition for data of all 39 observed NEAs. The data used to create this figure are available.

(The complete figure set (39 images) is available.)
| Object     | Obs. (UT) | Disc. Date | $\Delta D^a$ (days) | Obs. Duration (h:mm) | $H^b$ (mag) | $V$ (mag) | $V - R$ (mag) | $V - I$ (mag) | Amplitude$^c$ (mag) | Rot. Period$^d$ (minutes) | S-type | X-type | C-type | D-type | PHA |
|------------|-----------|------------|---------------------|----------------------|-------------|-----------|---------------|---------------|---------------------|--------------------------|--------|-------|-------|-------|-----|
| 2016 XT1   | 07 Dec 2016 07:15:43:53 | 5 Dec 2016 | 4 | 1:30 | 19.7 | 20.12 | 0.09 ± 0.05 | 0.05 ± 0.05 | >0.21 | >90 | 0.84 | 0.08 | 0.07 | 0.01 | N |
| 2016 CP32  | 20 Feb 2017 19:43:56 | 15 Feb 2017 | 6 | 1:42 | 23.9 | 20.14 | −0.01 ± 0.09 | 0.08 ± 0.10 | >0.60 | >102 | 0.26 | 0.38 | 0.18 | 0.19 | N |
| 2016 AE3   | 11 Jan 2017 19:29:12 | 15 Jan 2017 | 02 | 5:09 | 21.8 | 19.55 | 0.28 ± 0.15 | 0.15 ± 0.16 | >1.13 | >59 | 0.91 | 0.01 | 0.03 | 0.04 | Y |
| 2016 CJ1   | 12 Feb 2017 22:06:04 | 02 Feb 2017 | 11 | 1:08 | 19.2 | 20.81 | −0.17 ± 0.26 | −0.41 ± 0.31 | >0.65 | >68 | 0.05 | 0.04 | 0.90 | 0.02 | N |
| 2016 WJ1   | 29 Nov 2016 22:30:43 | 19 Nov 2016 | 11 | 1:47 | 21.3 | 18.08 | 0.00 ± 0.02 | 0.07 ± 0.03 | 0.20 ± 0.04 | 20.0 ± 0.9 | 0.09 | 0.85 | 0.05 | 0.01 | Y |
| 2016 WO1   | 01 Dec 2016 03:37:53 | 19 Nov 2016 | 13 | 1:02 | 19.9 | 20.10 | 0.18 ± 0.09 | −0.01 ± 0.15 | >0.40 | >62 | 0.75 | 0.01 | 0.22 | 0.02 | N |
| 2016 WP    | 01 Dec 2016 19:30:24 | 18 Nov 2016 | 14 | 1:08 | 21.9 | 20.82 | 0.02 ± 0.19 | −0.26 ± 0.30 | >0.89 | >68 | 0.17 | 0.06 | 0.73 | 0.04 | N |
| 2016 YM1   | 05 Jan 2017 19:49:43 | 22 Dec 2016 | 15 | 1:18 | 22.1 | 20.41 | 0.11 ± 0.14 | 0.27 ± 0.14 | 1.07 ± 0.19 | 28.2 ± 2.1 | 0.63 | 0.05 | 0.01 | 0.30 | N |
| 2017 CS    | 16 Feb 2017 02:08:12 | Dec 2016 | 15 | 1:43 | 19.4 | 20.54 | 0.04 ± 0.17 | 0.05 ± 0.24 | >0.79 | >103 | 0.37 | 0.13 | 0.33 | 0.17 | Y |
| 2017 CO5   | 28 Feb 2017 00:31:53 | Feb 2017 | 16 | 0.59 | 20.1 | 20.52 | 0.22 ± 0.13 | 0.09 ± 0.18 | >0.31 | >59 | 0.83 | 0.02 | 0.10 | 0.05 | N |
| 2017 BL6   | 11 Feb 2017 19:34:03 | 26 Jan 2017 | 17 | 1:07 | 21.1 | 20.36 | 0.05 ± 0.18 | 0.23 ± 0.17 | >0.83 | >67 | 0.47 | 0.13 | 0.06 | 0.34 | N |
| 2017 BG85  | 17 Feb 2017 21:40:52 | 26 Jan 2017 | 21 | 1:00 | 18.9 | 20.04 | 0.04 ± 0.08 | −0.15 ± 0.07 | >0.43 | >60 | 0.08 | 0.01 | 0.91 | 0.00 | N |
| 2017 BY93  | 17 Feb 2017 23:06:37 | 26 Jan 2017 | 23 | 1:45 | 23.2 | 18.31 | −0.11 ± 0.02 | −0.15 ± 0.05 | >0.14 | >105 | 0.00 | 0.00 | 1.00 | 0.00 | N |
| 2016 VU3   | 29 Nov 2016 20:00:35 | 06 Nov 2016 | 24 | 2:04 | 20.6 | 19.97 | −0.08 ± 0.08 | −0.15 ± 0.10 | >0.68 | >124 | 0.01 | 0.07 | 0.92 | 0.00 | N |
| 2016 YM    | 11 Jan 2017 21:29:00 | 18 Dec 2016 | 25 | 0.55 | 22.1 | 19.92 | −0.03 ± 0.12 | 0.22 ± 0.12 | >0.14 | >55 | 0.22 | 0.21 | 0.03 | 0.53 | N |
| 2016 VP4   | 06 Dec 2016 00:11:51 | 09 Nov 2016 | 27 | 1:02 | 24.2 | 20.65 | 0.25 ± 0.24 | 0.06 ± 0.21 | >0.92 | >62 | 0.72 | 0.05 | 0.15 | 0.07 | N |
| 2016 UJ101 | 08 Dec 2016 00:11:11 | 31 Oct 2016 | 38 | 0.55 | 20.4 | 19.76 | 0.13 ± 0.06 | 0.22 ± 0.07 | >0.18 | >55 | 0.82 | 0.01 | 0.00 | 0.17 | N |
| 2016 UU80  | 07 Dec 2016 21:13:55 | 29 Oct 2016 | 40 | 1:24 | 21.1 | 19.66 | 0.06 ± 0.04 | 0.01 ± 0.04 | 0.25 ± 0.06 | 88.3 ± 16.2 | 0.65 | 0.08 | 0.28 | 0.00 | N |
| 2017 AC5   | 15 Feb 2017 23:09:38 | 03 Jan 2017 | 44 | 0.54 | 19.9 | 19.47 | 0.09 ± 0.08 | 0.17 ± 0.10 | >0.77 | >54 | 0.64 | 0.08 | 0.02 | 0.26 | N |

Serendipitously Observed Targets

| Object     | Obs. (UT) | Disc. Date | $\Delta D^a$ (days) | Obs. Duration (h:mm) | $H^b$ (mag) | $V$ (mag) | $V - R$ (mag) | $V - I$ (mag) | Amplitude$^c$ (mag) | Rot. Period$^d$ (minutes) | S-type | X-type | C-type | D-type | PHA |
|------------|-----------|------------|---------------------|----------------------|-------------|-----------|---------------|---------------|---------------------|--------------------------|--------|-------|-------|-------|-----|
| 2016 XX23  | 15 Feb 2017 19:02:34 | 15 Dec 2016 | 53 | 1:07 | 17.6 | 20.95 | 0.31 ± 0.25 | −0.36 ± 0.34 | >0.96 | >67 | 0.43 | 0.01 | 0.55 | 0.01 | N |
| 2016 VC    | 28 Oct 2016 23:21:38 | 16 Mar 2015 | 593 | 2:24 | 17.5 | 19.96 | 0.03 ± 0.07 | 0.01 ± 0.06 | >0.40 | >144 | 0.39 | 0.25 | 0.35 | 0.01 | N |
### Table 1
(Continued)

| Object    | Obs. Mid-time (UT) | Obs. Duration (h:mm) | V (mag) | V – R (mag) | V – I (mag) | Amplitude (mag) | PHA |
|-----------|--------------------|----------------------|---------|-------------|-------------|-----------------|-----|
| 2009 RW6  | 01 Dec 2016 00:04:04 | 2007-07-31:00 05:45 | 17.9    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2007 PM4  | 30 Oct 2016 00:04:04 | 2007-09-16:07 54:00 | 20.75   | 0.3            | 0.2          | 0.6             | 0.99 |
| 2006 SX217| 29 Nov 2016 22:06:03 | 2006-07-14:06 25:00 | 19.8    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2003 UE7  | 22:03:31 | 2003-07-15:01 47:30 | 19.49   | 0.3            | 0.2          | 0.4             | 0.99 |
| 2002 WP   | 29 Oct 2016 01:04:28 | 2002-07-19:04 05:45 | 18.1    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2002 NQ7  | 06 Dec 2016 00:11:51 | 2002-07-19:04 05:45 | 17.5    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2002 KL6  | 01 Dec 2016 19:30:24 | 2002-07-19:04 05:45 | 17.5    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2001 TN41 | 30 Oct 2016 00:04:04 | 2001-07-19:04 05:45 | 16.5    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2000 VJ61 | 12 Feb 2017 19:32:38 | 2000-07-19:04 05:45 | 16.0    | 0.3            | 0.2          | 0.4             | 0.99 |
| 2000 GG162| 30 Oct 2016 23:12:24 | 2000-07-19:04 05:45 | 15.1    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1999 RO42 | 18 Feb 2017 03:31:53 | 2000-07-19:04 05:45 | 15.9    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1997 UP9  | 30 Oct 2016 00:11:51 | 1997-07-19:04 05:45 | 16.2    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1996 VK37 | 30 Oct 2016 23:12:24 | 1997-07-19:04 05:45 | 17.2    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1996 VX   | 01 Dec 2016 19:30:24 | 1997-07-19:04 05:45 | 16.3    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1984 SS   | 11 Jan 1997 19:25:05 | 1997-07-19:04 05:45 | 14.0    | 0.3            | 0.2          | 0.4             | 0.99 |
| 1982 RA1  | 13 Jan 1997 22:03:31 | 1997-07-19:04 05:45 | 16.5    | 0.3            | 0.2          | 0.4             | 0.99 |

**Notes.**

a Days between when object was discovered and when it was observed for this study.

b Obtained from [https://ssd.jpl.nasa.gov/horizons.cgi](https://ssd.jpl.nasa.gov/horizons.cgi).

c Lower limit shown in cases where observational duration was insufficient to observe entire light-curve period.

(This table is available in machine-readable form.)
source was selected, or that the target intersected a CCD defect or a star.

4. Analysis

4.1. Colors

The \( V - R \) and \( V - I \) colors of an NEA are calculated by simply subtracting the calibrated \( J \) and \( R \) magnitudes from the \( V \) magnitude. However, the magnitudes can vary in time because asteroids are rotating and not perfectly spherical bodies. They may also have non-uniformity in surface color. Therefore, the subtraction calculation is only strictly correct if the different filter magnitudes are measured at the exact same time. For this study, sequential filter images were taken (see Section 2) with the time difference between the mid-time approximately three minutes on average. On this timescale, the respective filter magnitude could change significantly, as some NEAs have rotation periods on the order of minutes (Thirouin et al. 2016).

To account for this, a linear interpolation was performed between adjacent \( V \) data points as described by Mommert et al. (2016). The interpolation was used to obtain a corrected \( V \) magnitude at times of inter-spaced non-\( V \) observations. Respective colors were derived by subtracting the non-\( V \) magnitudes from these interpolated \( V \) magnitudes. The final color is the weighted average (by error in respective data points) of all retrievable subtraction calculations in an observation. The final colors were also corrected for solar colors by subtracting the respective \( V - R \) and \( V - I \) solar colors (Binney & Merrifield 1998). The solar corrected colors of all observed NEAs are shown in Table 1 and plotted in Figure 4(c).

4.2. Taxonomic Classification

To classify each observed NEA as one of \( S \)-, \( X \)-, \( C \)-, or \( D \)-type asteroid, a Machine Learning (ML) algorithm approach was employed as described by Mommert et al. (2016). The ML algorithm was trained using asteroid colors that were synthesized from measured asteroid spectra taken from the MIT-UH-IRTF Joint Campaign for NEO Spectral Recognition. The database contains spectra of over 600 NEAs obtained with SpeX (Rayner et al. 2003) on NASA’s Infrared Telescope Facility. While most spectra range from 0.8 to 2.5 \( \mu m \), visible wavelength spectral data are also included from the MIT SMART observing program. The spectra were classified using the Bus-DeMeo taxonomy spectrum classification online routine and in the end, 74, 34, 28, and 6 reliable \( V - R \) and \( V - I \) colors of \( S \)-, \( X \)-, \( C \)-, and \( D \)-type asteroids, respectively, could be synthesized by using the above described approach.

The synthesized colors are plotted and shown in Figure 4(a) and a zoomed-in version is shown in Figure 4(b). The resultant classification boundaries generated by the ML algorithm are also indicated in these figures. The training of the ML algorithm was executed using the scikit-learn module (Pedregosa et al. 2011) for Python. The \( k \)-nearest neighbor (\( k = 5 \)) method was implemented, as in Mommert et al. (2016).

In order to account for uncertainties in the measurement of each of the observed NEA’s color, a Monte-Carlo approach was used where \( 10^6 \) pseudo-measured colors were randomly generated with a Gaussian distribution within the corresponding \( 1 \sigma \) uncertainties of each NEA’s real measured color. To illustrate this process, two examples are shown in Figure 4(d). Each of the \( 10^6 \) instances of each NEA was classified using the trained ML algorithm and the overall frequency of each taxonomic type was tallied. The classification probability for each taxonomic type was then calculated. The most likely (i.e., highest probability) taxonomic type was assigned to the NEA only if this probability was larger than 50% (see Table 1 for probabilities where bold text indicates the most likely classification). The assigned classifications are indicated in Figure 4(c) by means of the color of the data point (orange: \( S \)-type, blue: \( X \)-type, pink: \( C \)-type, yellow: \( D \)-type asteroid, and gray: undetermined).

4.3. Light Curves

Light curves were produced by combining the \( V \) magnitude data points with adjusted \( I \) and \( R \) magnitude data points. Adjustments were implemented by normalizing the original \( I \) and \( R \) magnitude data points to \( V \) magnitudes by adding the derived colors (see Section 4.1 for detail on how colors were derived). Examples of resultant light curves are shown as the bottom curves in Figures 3(a)–(d) with the original \( V \) data and adjusted \( R \) and \( I \) data inter-spaced.

Only a fraction of the observed NEAs (e.g., 2017 AJ57 in Figure 3(a)) had rotational periods short enough to produce a light curve with a resolvable light-curve period within the \( \sim 1 \) hr observation. Most observations only produced light curves covering a fraction of the rotational period (e.g., 2017 AC5 in Figure 3(b)), and therefore in most cases, only lower limits on both the light curve amplitude (\( A \)) and rotation period (\( P \)) could be determined. However, 6 of the 39 targets had resolvable light-curve periods within the observation time.

To determine which targets had resolvable light-curve periods, the light curve data for each NEA were analyzed using the NASA Exoplanet Science Institute’s periodogram online tool. Designed to generate periodograms from the Kepler and K2 light curve data archive, the tool is also able to generate periodograms of user-uploaded data. The tool makes use of the Lomb–Scargle method, a least-squares spectral analysis, to estimate a frequency spectrum and thereby generates a periodogram. Figure 5(b) shows the periodogram generated from the light curve data of 2016 WJ1 with a distinct peak at 10 minutes, suggesting a possible periodicity at this interval. The uncertainty of this periodicity is determined by fitting a Gaussian function to the periodogram peak and using the rms width (\( \sigma \)) as the uncertainty (see superimposed black curve and \( \sigma \) of the fitted function). The confidence in the periodogram peak is also indicated and calculated using the false alarm probability formulation from Zechmeister & Kürster (2009). Figure 5(c) shows the folded representation of the original light curve data using the 10.00 minute folding interval, resulting in a light curve with a convincing completely resolvable oscillation. Using this folded data, the amplitude is calculated using the difference between magnitudes highlighted with the gray triangle symbols. The triangles are situated where the mean of two adjacent data points have the minimum/maximum magnitude.

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12 http://smass.mit.edu/minus.html
13 http://smass.mit.edu/smass.html
14 http://smass.mit.edu/busdemeoclass.html
15 https://exoplanetarchive.ipac.caltech.edu/cgi-bin/Pgram/nph-pgram
See electronic edition of Figure 5 for all six targets that produced periodograms with a distinct peak.) The light-curve periods obtained from the periodogram peak position and the amplitudes determined from the folded data are recorded in Table 1 for these six targets. Note that in Table 1, the rotation period is indicated, which is double the light-curve period. For the remaining targets, the lower limit of the rotation period (i.e., the observational duration) and the lower limit of the amplitude are used to complete Table 1. In the latter case, the amplitude lower limited is calculated in the same way as before, but instead the original unfolded data are used (see gray triangles in Figure 3).

5. Discussion

5.1. Compositional Distribution

One of the primary aims of this study is to derive the compositional distribution of NEAs as a function of size. Figure 6 shows the classified target data points from Figure 4(c) plotted as a function of absolute magnitude \((H)\). The size estimates at various \(H\) magnitudes (based on an albedo of 0.2) are also indicated. This relatively sparse plot suggests that there is no significant difference in ratio between “stony” S-type and “not-stony” (C+X+D)-type asteroids across the observed asteroid size range. The plot does suggest that the ratio is
slightly in favor of S-type for larger asteroids and that X- and D-type could perhaps favor smaller asteroids.

However, Figure 6 is based on discrete classification, i.e., only the highest classification probability in Table 1 is considered. A more statistically correct distribution is obtained by calculating the fractions based on the summation of the probabilities in Table 1 for each respective class type. The result of this summation is shown in Figure 7. The fraction of S-type asteroids in our observed population is ∼56% for large (15 < H < 20) NEAs and ∼43% for smaller (20 ≤ H < 25) NEAs. Within the error bars, there is no difference between these two values, and in both size bins, our result is in agreement with Mommert et al. (2016). Therefore, our data suggest a roughly 50/50 split in numbers between “stony” S-type and “not-stony” (C+X+D)-type asteroids across the observed asteroid size range.
The fraction of meteorites that have compositions similar to S-type asteroids is more than 80% (Harvey & Cassidy 1989), well above our observed ∼50% for S-type asteroids. Most meteorites are generated from NEAs that are around 10 m in size (i.e., \( H \approx 27 \)), which is slightly smaller than the smallest size bin shown in Figure 7. However, Momert et al. (2016) show a third bin for \( 25 \leq H < 30 \) showing an S-type fraction of around 40% and Hinkle et al. (2014) also find that the S-type fraction is low and decreasing at small NEA sizes. It has been proposed (Reddy et al. 2016) that the discrepancy between meteorites and optically observed distributions could be a result of atmospheric filtering with the stony-like material in S-type asteroids more likely to survive atmospheric entry and reach the ground than that of the more primitive and fragile material present in D- and C-type asteroids. Our results strengthen this argument, as they are not consistent with an S-type fraction of 80%.

Both Momert et al. (2016) and our results do not account for bias inherent to our target sample. Selecting from optically discovered targets means our sample targets mostly have medium to high surface albedos. This favors S-type over C-type asteroids (Thomas et al. 2011). This effect would lead to an overestimation of the fraction of S-type asteroids, which strengthens our argument even further.

5.2. Light Curve Data

Out of the 39 observed NEAs, lower limits on the light curve amplitude and rotation period are determined for 33 targets. The rotation period lower limits of these 33 targets that are shown in Table 1 are all ≥1 hr and are generally consistent with the overall distribution of previously reported NEA light curve properties: many asteroids with rotational periods larger than 1 hr have been reported for asteroids in our size range (15 ≤ H ≤ 25; Thirouin et al. 2016).

For the six targets that had resolvable light curves, the three smallest targets—2016 YM1 (\( P_{\text{rot}} = 28.2 \) minutes, \( H = 22.1 \)), 2016 WJ1 (\( P_{\text{rot}} = 20.0 \) minutes, \( H = 21.3 \)), and 2016 UU80 (\( P_{\text{rot}} = 88.3 \) minutes, \( H = 21.1 \))—have periods and sizes consistent with previously reported observations and fall below the 100 Pa lower limit cohesion curve for lunar regolith (Thirouin et al. 2016). Two of the three larger targets have rotation periods larger than the theoretical breakup rotation period of ~2 hr and are also consistent with previously reported observations (Thirouin et al. 2016). The remaining large target, 2000 VJ61 (\( P_{\text{rot}} = 77.3 \) minutes, \( H = 16.0 \)), has a rotation period shorter than any previously observed targets of this size, although it still falls below the 1000 Pa higher limit cohesion curve for lunar regolith. However, the calculated light-curve period is only half the observational duration, which suggests some aliasing and that we have not detected the entire period. Also, the confidence in the periodogram peak is also only 72.9%. Further observations of this target for longer times may prove interesting, because confirming this unexpectedly short rotation period would be extraordinary for such large asteroid.

Our data also shows that 2016 YM1, which is rotating relatively fast, also has a large amplitude (\( A \approx 1 \) mag) in the light curve. An amplitude of 1.0 would suggest an \( a/b \) ratio (longest axis to middle axis) of 2.5, which would mean 2016 YM1 is not only fast rotating but is an elongated object as well.

6. Conclusion

The VRI spectrophotometric results of 39 NEAs observed with the Sutherland, South Africa, node of KMTNet have been presented. Our broadband spectrophotometry in combination with an ML algorithm allow us to classify 39 of the 39 observed target as either an S-, C-, X-, or D-type asteroid. Our data suggest that the ratio between “stony” S-type NEAs and “not-stony” (C+X+D)-type NEAs, with \( H \) magnitudes between 15 and 25, is roughly 1:1, which is an agreement with previously published survey studies. However, this ratio is not consistent with an S-type fraction of 80% shown in collected meteorites, and therefore our results supports the idea of atmospheric filtering that leads to a preference for S-type meteorite survival through the atmosphere.

Our ~1 hr light curve data of each observed NEA allowed us to place lower limit constraints on the rotational period of 33 NEAs and resolve the rotational periods of six NEAs. The lower limit rotational periods, together with the size of the relevant NEAs, are consistent with previously published observations of NEAs with similar sizes. For three small NEAs with resolvable periods, our data are also consistent with previously published observations of NEAs with similar sizes. For the three large NEAs with resolvable periods, our data are consistent for two of the targets. For the remaining large target, our results are inconsistent. However, the confidence in the periodogram peak is relatively low for this target. Therefore, there are justified doubts on the legitimacy of this large NEAs’ calculated rotation period.

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ORCID iDs

M. Momert https://orcid.org/0000-0002-8132-778X
D. E. Trilling https://orcid.org/0000-0003-4580-3790
J. L. Hora https://orcid.org/0000-0002-5599-4650

References

Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton, NJ: Princeton Univ. Press)
Borovička, J., Spurz, P., Brown, P., et al. 2013, Natur, 503, 235
Bottke, W. F., Jedicke, R., Morbidelli, A., Petit, J-M., & Gladman, B. 2000, Sci, 288, 2190
Brown, P. G., Assink, J. D., Astiz, L., et al. 2013, Natur, 503, 238
Cheng, A., Michel, P., Jutzi, M., et al. 2016, P&SS, 121, 27
DeMeo, F. E., Binzel, R. P., Slivan, S. M., & Bus, S. J. 2009, Icar, 202, 160
Elvis, M. 2012, Natur, 485, 549
Galache, J., Beeson, C., McLeod, K., & Elvis, M. 2015, P&SS, 111, 155
Granvik, M., Morbidelli, A., Vokrouhlický, D., et al. 2017, A&A, 598, A52
Harvey, R. P., & Cassidy, W. A. 1989, Metic, 24, 9
Hinkle, M., Moskovitz, N., & Trilling, D. 2014, in AAS/DPS Meeting 46 Abstracts, 213.07
Kim, S.-L., Lee, C.-U., Park, B.-G., et al. 2016, JKAS, 49, 37
Lauretta, D. S., Beshore, E., Boynton, W. V., et al. 2017, SSV, 1
Mainzer, A., Grav, T., Bauer, J., et al. 2011, Apl, 743, 156
Mommert, M. 2017, A&C, 18, 47
Mommert, M., Trilling, D. E., Borth, D., et al. 2016, AJ, 151, 98
Pedregosa, F., Varoquaux, G., Gramfort, A., et al. 2011, Journal of Machine Learning Research, arXiv:1201.0490
Rayner, J., Toomey, D., Onaka, P., et al. 2003, PASP, 115, 362
Reddy, V., Sanchez, J. A., Bottke, W. F., et al. 2016, AJ, 152, 162
Reddy, V., Vokrouhlický, D., Bottke, W. F., et al. 2015, Icar, 252, 129
Sanchez, P., Colombo, C., Vasile, M., & Radice, G. 2009, JGCD, 32, 121
Thirouin, A., Moskovitz, N., Binzel, R. P., et al. 2016, AJ, 152, 163
Thomas, C. A., Trilling, D. E., Emery, J. P., et al. 2011, AJ, 142, 85
Tsuda, Y., Yoshikawa, M., Abe, M., Minamino, H., & Nakazawa, S. 2013, A&A, 91, 356
Yano, H., Kubota, T., Miyamoto, H., et al. 2006, Sci, 312, 1350
Zechmeister, M., & Kürster, M. 2009, A&A, 496, 577