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# NEOROCKS project: surface properties of small near-Earth asteroids

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## ABSTRACT

We present new results of the observing program which is a part of the NEOROCKS project aimed to improve knowledge on physical properties of near-Earth Objects (NEOs) for planetary defense. Photometric observations were performed using the 1.2-m telescope at the Haute-Provence observatory (France) in the *BVRI* filters of the Johnson–Cousins photometric systems between June 2021 and April 2022. We obtained new surface colours for 42 NEOs. Based on the measured colours, we classified 20 objects as S-complex, nine as C-complex, nine as X-complex, two as D-type, one object as V-type, and one object remained unclassified. For all the observed objects, we estimated their absolute magnitudes and diameters. Combining these new observations with the previously acquired data within the NEOROCKS project extended our data set to 93 objects. The majority of objects in the data set with diameters  $D < 500$  m belongs to a group of silicate bodies, which could be related to observational bias. Based on MOID and  $\Delta V$  values we selected 14 objects that could be accessible by a spacecraft. Notably, we find D-type asteroid (163014) 2001 UA5 and A-type asteroid 2017 SE19 to be of particular interest as possible space mission targets.

**Key words:** Techniques: photometric – Surveys – Minor planets, asteroids: general.

## 1 INTRODUCTION

A population of near-Earth objects (NEOs) is believed to be brought into their current location from the asteroid belt due to the Yarkovsky effect and gravitational interactions with Jupiter and Saturn and defined by perihelion distance  $q < 1.3$  au (Wisdom 1983; Bottke et al. 2006; Granvik et al. 2017). Such proximity to our planet gives us a chance to study these asteroids down to several metres in diameter, whereas main-belt asteroids could be reached only down to hundreds of metres by the means of ground-based observations. Investigation of NEOs provides us with an opportunity to better understand the evolution of the Solar system, and the processes that

took place at the early stages of its formation. Notably, NEOs are also a threat to humanity due to potential collision hazard (e.g. Perna, Barucci & Fulchignoni 2013; Perna et al. 2016). In particular, NEOs with minimum orbital intersection distance MOID  $< 0.05$  au and absolute magnitude  $H < 22$  are classified as potentially hazardous asteroids (PHAs).

The number of discovered NEOs is constantly growing, but the number of NEOs with known physical properties is very small. According to the Light Curve Database (Warner, Harris & Pravec 2009, updated 2021, December 14), rotational period and/or surface colour is known for 2117 objects, which is only about 7 per cent of the discovered NEOs. In addition, the majority of these objects are large NEOs. The rate at which new NEOs are being discovered only increases this gap. Thus, there is a need for dedicated surveys that would focus on investigating the physical properties of NEOs, particularly the smallest members of the population.

The whole variety of compositional classes is found among NEOs, with majority of the population (from 40 to 70 per cent) represented by silicate S-complex asteroids (Ieva et al. 2018, 2020; Lin et al. 2018; Perna et al. 2018; Binzel et al. 2019; Devogèle et al. 2019; Popescu et al. 2019). However, the recent work by Marsset et al. (2022) that presented a debiased distribution of NEOs suggests that the low-albedo carbonaceous asteroids might be underrepresented, and the amount of silicate and carbonaceous asteroids is nearly equal.

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**Table 1.** Observational circumstances and results.

|    | Object              | Date       | <i>r</i> , au | $\Delta$ , au | $\alpha$ , ° | <i>V</i> mag | <i>B</i> − <i>V</i> | <i>V</i> − <i>R</i> | <i>V</i> − <i>I</i> | Taxon | <i>H</i> | <i>D</i> , m |
|----|---------------------|------------|---------------|---------------|--------------|--------------|---------------------|---------------------|---------------------|-------|----------|--------------|
| 1  | (12923) Zephyr      | 27/11/2021 | 1.408         | 0.618         | 37.1         | 17.21 ± 0.02 | 0.94 ± 0.04         | 0.45 ± 0.03         | 0.70 ± 0.04         | Q/S   | 16.1     | 2060 ± 10*   |
| 2  | (87024) 2000 JS66   | 09/06/2021 | 1.063         | 0.166         | 69.1         | 17.72 ± 0.02 | 0.71 ± 0.02         | 0.37 ± 0.02         | 0.83 ± 0.04         | X     | 19.0     | 670-1080     |
| 3  | (89958) 2002 LY45   | 11/06/2021 | 1.305         | 0.362         | 31.9         | 16.94 ± 0.02 | 0.75 ± 0.04         | 0.47 ± 0.02         | 0.75 ± 0.02         | Q/S   | 17.3     | 1100-1330    |
| 4  | (138971) 2001 CB21  | 28/01/2022 | 1.165         | 0.251         | 39.6         | 17.43 ± 0.03 | 0.92 ± 0.04         | 0.39 ± 0.03         | 0.82 ± 0.04         | X     | 18.4     | 940-1190     |
|    |                     | 29/01/2022 | 1.160         | 0.242         | 39.5         | 17.24 ± 0.03 | 0.84 ± 0.04         | 0.43 ± 0.02         | 0.79 ± 0.03         | –     | –        | –            |
| 5  | (140158) 2001 SX169 | 09/06/2021 | 1.097         | 0.128         | 47.5         | 15.89 ± 0.01 | 0.76 ± 0.03         | 0.46 ± 0.02         | 0.82 ± 0.02         | Xe/X  | 18.4     | 566 ± 10*    |
| 6  | (143649) 2003 QQ47  | 02/10/2021 | 1.068         | 0.173         | 63.1         | 16.12 ± 0.02 | 0.90 ± 0.03         | 0.52 ± 0.02         | 0.86 ± 0.02         | S     | 17.5     | 950-1160     |
| 7  | (162913) 2001 MT18  | 09/06/2021 | 1.017         | 0.206         | 83.8         | 18.06 ± 0.02 | –                   | 0.55 ± 0.02         | 1.05 ± 0.03         | D     | 18.5     | 940-1310     |
| 8  | (163692) 2003 CY18  | 05/04/2022 | 1.307         | 0.355         | 26.7         | 18.03 ± 0.02 | 0.84 ± 0.03         | 0.49 ± 0.02         | 0.94 ± 0.03         | S     | 18.5     | 630-760      |
| 9  | (318160) 2004 QZ2   | 27/01/2022 | 1.389         | 0.407         | 5.7          | 17.46 ± 0.02 | 0.81 ± 0.02         | 0.47 ± 0.02         | 0.77 ± 0.03         | Sq/S  | 18.2     | 690-840      |
| 10 | (363027) 1998 ST27  | 01/10/2021 | 1.152         | 0.194         | 36.1         | 17.72 ± 0.02 | 0.78 ± 0.03         | 0.42 ± 0.02         | 0.75 ± 0.03         | C     | 19.6     | 578 ± 228*   |
|    |                     | 02/10/2021 | 1.146         | 0.192         | 37.5         | 17.78 ± 0.02 | 0.73 ± 0.02         | 0.39 ± 0.02         | 0.72 ± 0.03         | –     | –        | –            |
| 11 | (363599) 2004 FG11  | 05/04/2022 | 1.082         | 0.102         | 35.7         | 17.57 ± 0.02 | 0.76 ± 0.02         | 0.43 ± 0.02         | 0.74 ± 0.02         | Xe/X  | 21.2     | 152 ± 3*     |
|    |                     | 06/04/2022 | 1.069         | 0.090         | 39.5         | 17.18 ± 0.02 | 0.77 ± 0.02         | 0.43 ± 0.02         | 0.71 ± 0.02         | –     | –        | –            |
| 12 | (366746) 2004 LJ    | 10/06/2021 | 1.112         | 0.142         | 44.5         | 17.80 ± 0.02 | –                   | 0.51 ± 0.03         | 0.76 ± 0.03         | Sq/S  | 20.15    | 260-320      |
| 13 | (374855) 2006 VQ13  | 26/11/2021 | 1.138         | 0.176         | 28.6         | 17.85 ± 0.02 | 0.71 ± 0.04         | 0.44 ± 0.03         | 0.82 ± 0.10         | X     | 20.1     | 370-590      |
|    |                     | 27/11/2021 | 1.145         | 0.182         | 27.5         | 17.89 ± 0.03 | –                   | 0.50 ± 0.03         | 0.87 ± 0.03         | –     | –        | –            |
| 14 | (388945) 2008 TZ3   | 05/04/2022 | 1.185         | 0.203         | 22.6         | 18.33 ± 0.03 | 0.73 ± 0.03         | 0.41 ± 0.03         | 0.68 ± 0.04         | Cg/C  | 20.3     | 370-480      |
| 15 | (410195) 2007 RT147 | 28/01/2022 | 1.361         | 0.383         | 9.2          | 17.32 ± 0.02 | 0.75 ± 0.04         | 0.45 ± 0.03         | 0.66 ± 0.04         | Q/S   | 18.2     | 580-700      |
| 16 | (415029) 2011 UL21  | 10/06/2021 | 1.181         | 0.540         | 59.1         | 16.90 ± 0.02 | 0.82 ± 0.04         | 0.47 ± 0.02         | 0.86 ± 0.03         | Q/S   | 15.7     | 1900-2310    |
|    |                     | 11/06/2021 | 1.191         | 0.542         | 58.2         | 16.90 ± 0.02 | 0.78 ± 0.04         | 0.49 ± 0.02         | 0.88 ± 0.03         | –     | –        | –            |
| 17 | (450263) 2003 WD158 | 08/06/2021 | 1.007         | 0.072         | 94.6         | 16.91 ± 0.02 | –                   | 0.52 ± 0.03         | 0.90 ± 0.04         | S     | 19.4     | 460-550      |
|    |                     | 10/06/2021 | 1.014         | 0.066         | 89.1         | 16.77 ± 0.02 | 0.84 ± 0.03         | 0.48 ± 0.02         | 0.86 ± 0.03         | –     | –        | –            |
| 18 | (475665) 2006 VY13  | 06/04/2022 | 1.338         | 0.456         | 35.3         | 17.72 ± 0.02 | –                   | 0.35 ± 0.03         | 0.65 ± 0.03         | C     | 17.4     | 1630-2070    |
| 19 | (491567) 2012 RG3   | 10/06/2021 | 1.242         | 0.382         | 46.1         | 18.34 ± 0.03 | –                   | 0.41 ± 0.03         | 0.92 ± 0.03         | D     | 18.3     | 1030-1430    |
| 20 | (495615) 2015 PQ291 | 09/06/2021 | 1.215         | 0.334         | 46.5         | 17.37 ± 0.02 | 0.83 ± 0.03         | 0.47 ± 0.02         | 0.88 ± 0.03         | S     | 17.6     | 790-960      |
| 21 | (506459) 2002 AL14  | 29/01/2022 | 1.127         | 0.152         | 19.8         | 15.10 ± 0.01 | 0.88 ± 0.02         | 0.50 ± 0.02         | 0.92 ± 0.02         | S     | 18.0     | 760-920      |
| 22 | (516396) 2000 WY28  | 26/11/2021 | 1.165         | 0.180         | 7.0          | 17.88 ± 0.02 | 0.90 ± 0.05         | 0.36 ± 0.05         | 0.67 ± 0.05         | C     | 20.8     | 430-550      |
| 23 | (613291) 2005 YX128 | 28/01/2022 | 1.072         | 0.176         | 56.0         | 17.35 ± 0.02 | 0.80 ± 0.03         | 0.42 ± 0.02         | 0.72 ± 0.03         | C     | 18.9     | 710-910      |
| 24 | (613403) 2006 GB    | 04/04/2022 | 1.056         | 0.107         | 55.8         | 17.39 ± 0.02 | 0.77 ± 0.02         | 0.40 ± 0.02         | 0.77 ± 0.03         | C     | 20.1     | 390-500      |
| 25 | 2002 TP69           | 26/11/2021 | 1.041         | 0.057         | 17.7         | 16.81 ± 0.01 | 0.84 ± 0.03         | 0.50 ± 0.02         | 0.93 ± 0.02         | S     | 22.0     | 120-150      |
|    |                     | 27/11/2021 | 1.043         | 0.059         | 16.3         | 16.85 ± 0.02 | 0.87 ± 0.03         | 0.51 ± 0.02         | 0.92 ± 0.02         | –     | –        | –            |
| 26 | 2009 CC3            | 05/04/2022 | 1.045         | 0.143         | 68.1         | 17.38 ± 0.02 | 0.96 ± 0.04         | 0.52 ± 0.02         | 0.77 ± 0.02         | S     | 19.1     | 460-550      |
| 27 | 2010 TV149          | 04/04/2022 | 1.079         | 0.177         | 60.3         | 17.08 ± 0.02 | 0.78 ± 0.03         | 0.42 ± 0.02         | 0.79 ± 0.03         | X     | 18.5     | 670-1080     |
| 28 | 2010 WQ7            | 28/01/2022 | 1.130         | 0.248         | 48.8         | 18.26 ± 0.02 | 0.75 ± 0.04         | 0.51 ± 0.03         | 0.88 ± 0.03         | S/S   | 19.2     | 630-760      |
| 29 | 2011 YQ10           | 26/11/2021 | 1.308         | 0.324         | 6.9          | 17.83 ± 0.02 | 0.72 ± 0.02         | 0.49 ± 0.02         | 0.63 ± 0.02         | Q/S   | 19.1     | 440-530      |
| 30 | 2017 UW42           | 27/01/2022 | 1.268         | 0.336         | 28.2         | 17.34 ± 0.01 | 0.87 ± 0.02         | 0.50 ± 0.02         | 0.91 ± 0.02         | S     | 17.9     | 760-920      |
| 31 | 2018 CW13           | 28/01/2022 | 1.177         | 0.193         | 5.0          | 17.03 ± 0.02 | 0.80 ± 0.03         | 0.43 ± 0.02         | 0.72 ± 0.03         | Cg/C  | 19.9     | 450-570      |
| 32 | 2021 JQ24           | 27/11/2021 | 1.378         | 0.420         | 18.0         | 17.53 ± 0.02 | 0.67 ± 0.03         | 0.40 ± 0.02         | 0.73 ± 0.03         | Xc/X  | 17.8     | 1010-1630    |
| 33 | 2021 LN3            | 11/06/2021 | 1.103         | 0.093         | 19.2         | 17.22 ± 0.02 | –                   | 0.46 ± 0.03         | 0.73 ± 0.05         | Q/S   | 21.2     | 150-180      |
| 34 | 2021 SR41**         | 06/04/2022 | 1.144         | 0.275         | 52.5         | 19.14 ± 0.03 | 0.82 ± 0.03         | 0.39 ± 0.03         | 0.72 ± 0.03         | C     | 19.7     | 470-600      |
| 35 | 2021 VM25**         | 08/04/2022 | 1.043         | 0.073         | 53.1         | 16.71 ± 0.02 | 0.71 ± 0.03         | 0.49 ± 0.02         | 0.86 ± 0.03         | S     | 20.4     | 360-500      |
| 36 | 2021 WX3            | 04/04/2022 | 1.116         | 0.132         | 27.1         | 17.48 ± 0.02 | 0.71 ± 0.02         | 0.38 ± 0.02         | 0.67 ± 0.02         | C     | 20.4     | 360-450      |
| 37 | 2022 BH3            | 29/01/2022 | 0.998         | 0.016         | 31.6         | 18.57 ± 0.02 | 0.91 ± 0.03         | 0.51 ± 0.02         | –                   | S     | 26.3     | 10-20        |
| 38 | 2022 BK             | 27/01/2022 | 1.037         | 0.057         | 23.4         | 17.66 ± 0.02 | –                   | 0.43 ± 0.02         | 0.82 ± 0.03         | X     | 22.7     | 110-170      |
| 39 | 2022 BQ3            | 05/04/2022 | 1.147         | 0.218         | 43.5         | 17.72 ± 0.02 | 1.00 ± 0.03         | 0.5 ± 0.02          | 0.64 ± 0.03         | V     | 19.1     | 240-280      |
| 40 | 2022 DC5**          | 06/04/2022 | 1.039         | 0.068         | 53.6         | 18.62 ± 0.02 | –                   | 0.43 ± 0.02         | 0.70 ± 0.03         | X     | 22.4     | 80-90        |
| 41 | 2022 GC1**          | 04/04/2022 | 1.112         | 0.117         | 15.9         | 18.94 ± 0.02 | –                   | 0.52 ± 0.02         | 0.87 ± 0.03         | S     | 22.5     | 80-100       |
| 42 | 2022 GY2**          | 08/04/2022 | 1.051         | 0.059         | 31.8         | 17.04 ± 0.03 | –                   | 0.38 ± 0.03         | –                   | –     | 21.8     | 120-190      |

Notes.\* Measured by NEOWISE survey (Mainzer et al. 2019).

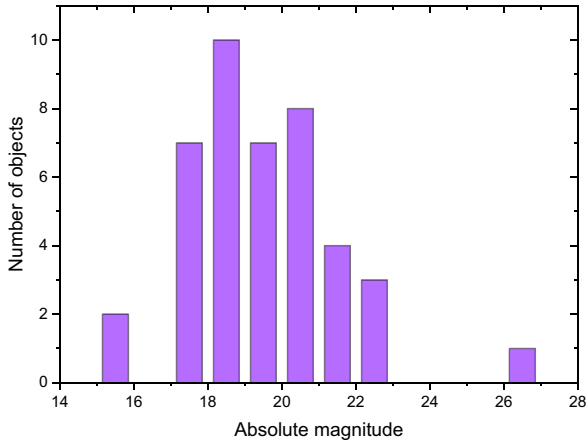
\*\*These objects were observed as part of the Rapid Response Experiment (Perna et al., in preparation).

Here we present the results of new observations conducted within the framework of the NEOROCKS project, which aims to characterize small NEOs by obtaining their surface colours and classify them into taxonomic classes.

In Section 2, we describe the observations and main results. Section 3 presents taxonomic classification of the observed NEOs. We present the analysis and discuss the results in Section 4. Finally, the summary and conclusions of this work are presented in Section 5.

## 2 OBSERVATIONS AND RESULTS

New photometric data presented in this work were obtained during several observational runs between June 2021 and April 2022 using the 1.2-m telescope at the Haute-Provence observatory (OHP), located in France. The telescope is equipped with a 2048 × 2048 Andor Ikon L 936 CCD camera that has a field of view of 13.1 × 13.1 arcmin. A 2 × 2 binning that was applied throughout all observing runs gave a 0.77 arcsec px<sup>−1</sup> scale.



**Figure 1.** Absolute magnitude distribution of the observed NEOs.

The selection of the targets was similar to the previous work (Hromakina et al. 2021): We prioritized objects with higher absolute magnitude (i.e. smaller objects) and PHAs. Additionally, newly discovered NEOs were also added to the priority list, because the discovery apparition is followed by a small window when the object is available for characterization (e.g. Galache et al. 2015).

Observations were obtained in  $B-V-R-I$  filters of the Johnson–Cousins photometric system. Each object was observed for about an hour, which, depending on the exposure time from 30 s to 3 min, resulted in 3–15 images in each filter. The images in each filter were taken sequentially in order to minimize possible magnitude variation due to the rotation of an object.

Data reduction was done following the same approach that was described in Hromakina et al. (2021), which includes bias subtraction and flat-field correction. The instrumental magnitudes were measured for the target and field stars using aperture photometry. Then, absolute calibration was done using magnitudes of field stars in the Pan-STARRS catalogue. To transform star magnitudes from the Sloan photometric system of the Pan-STARRS1 catalogue into the Johnson–Cousins system, we used transformational equations presented in Kostov & Bonev (2018).

We observed 42 small NEOs, about a quarter of which are recently discovered objects. Five objects observed during the April 2022 run were observed as part of the Rapid Response Experiment (Perna et al., in preparation), which is another objective of the NEOROCKS programme. Nearly 40 per cent of the observed NEOs (16 out of 42) are classified as PHAs. Table 1 contains the photometry results, estimated absolute magnitudes and diameters, and observational circumstances of our data. The orbital elements of the observed asteroids are presented in Table A1 of the Appendix A.

Absolute magnitudes ( $H$ ) given in Table 1 were calculated using our measurements of  $V$  magnitudes via the online tools for  $H$ ,  $G_1$ ,  $G_2$  photometric system.<sup>1</sup> It was shown that the one-parameter version of the  $H$ ,  $G_1$ ,  $G_2$  function can give reliable results even in the case of only one magnitude measurement (Penttilä et al. 2016). We compared our absolute magnitudes with the values presented in the Minor Planetary Center (MPC) and found generally good agreement. For three asteroids 2010 WQ7, 2022 BQ3, and 2022 DC5 the discrepancies exceed 0.5 mag. Further observations are needed to find possible reasons for these discrepancies. Absolute magnitude distribution of the sample is shown in Fig. 1. Almost all

of the observed NEOs fall into the 17–23 mag range, with the largest absolute magnitude reaching  $H \sim 26$ .

To estimate the diameters of the observed objects we used the obtained absolute magnitudes and albedos of the respective taxonomic classes from Ryan & Woodward (2010). For the unclassified object 2022 GY2 we assumed S-complex taxonomic class. For 4 out of 42 NEOs in our sample the diameters were measured by the NEOWISE survey (Mainzer et al. 2019). Our estimations are well-consistent with the measured values within the uncertainties. In Table 1, we provide the NEOWISE diameters for four asteroids.

Table 1 also contains the results of the taxonomic classification that was performed in this work and described in the next section.

### 3 TAXONOMY

Taxonomic classification was done using the obtained surface colours  $B-V$ ,  $V-R$ , and  $V-I$ , which were transformed into reflectances using the following equation:

$$R(\lambda) = 10^{-0.4[(M_\lambda - M_V) - (M_\lambda - M_V)_\odot]}, \quad (1)$$

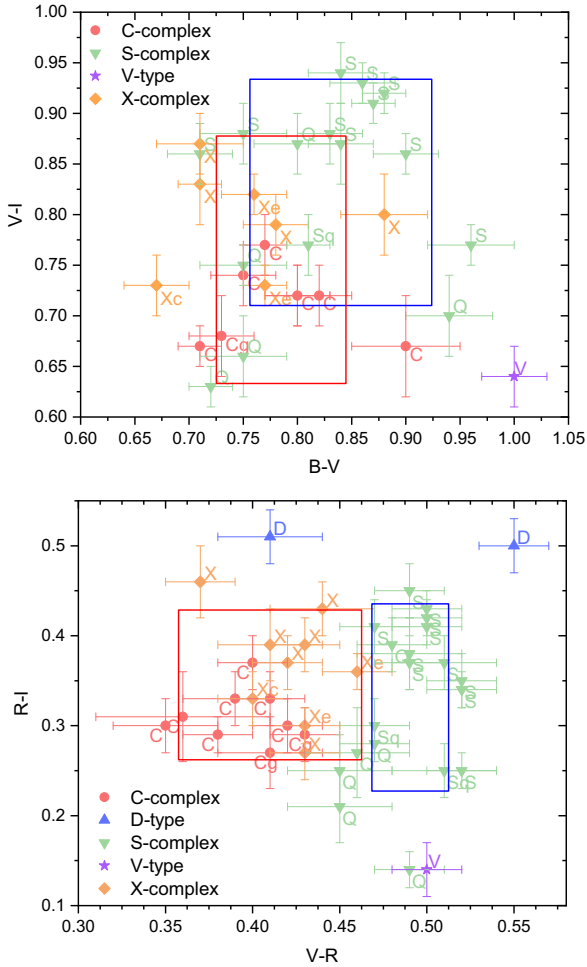
where  $(M_\lambda - M_V)$  and  $(M_\lambda - M_V)_\odot$  are the colours of the object and the Sun at the wavelength  $\lambda$ , respectively. Solar colours were taken from Holmberg, Flynn & Portinari (2006). The obtained reflectance was normalized at the central wavelength of the  $V$ -filter. Then, using the M4AST service (Popescu, Birlan & Nedelcu 2012; Birlan et al. 2016), the resulting spectra were compared to the mean spectra of the taxonomic classes in DeMeo classification (DeMeo et al. 2009). In the case when the object was observed for two nights the average surface colours were used for taxonomic classification. One asteroid from the data set, 2022 GY2, was not classified because only  $V-R$  colour was measured. As our taxonomic classification is based on only three or four data points, it is not nearly as precise as spectral data. Thus, in Table 1 we indicate the major taxonomic classes, such as S-complex, C-complex, X-complex, A-type, D-type, and V-type. However, in the case of an unambiguous match to a specific subtype according to Bus–DeMeo classification, we indicate both the subtype and the major type. Some asteroids in our sample revealed similarity with Q-type, first defined by (Tholen 1984) for a near-Earth asteroid and considered as an end member class in DeMeo et al. (2009). In our further analysis, we consider Q-type as a part of the S-complex. Fig. B1 in Appendix B shows individual reflectance spectra of asteroids together with the mean spectra of the best-matching taxonomic class.

We checked our classification using colour–colour plots (Fig. 2). Boxes in the figures represent  $1\sigma$  deviation of silicate and carbonaceous objects (see sect. 4). Some of the asteroids in the colour–colour diagrams seem to be ‘outliers’, so we looked more closely into these objects. Asteroid (162913) 2001 MT18 is classified as D-type and has very red surface colours. Taking into account that this NEO was observed at a large phase angle ( $83.8^\circ$ ), its very red colours may be a result of phase reddening (e.g. Schröder et al. 2014; Perna et al. 2018). Other S-complex ‘outliers’ are classified as Q-types, fresh-surfaced asteroids with more neutral slopes compared to S-type asteroids.

One more way to establish the reliability of the taxonomic classification is to compare the obtained results for the objects that were already classified based on more informative spectral data. Only two objects in this work, namely (12923) Zephyr and (506459) 2002 AL14 were previously classified by using spectral data as S-complex and L-type, respectively (Binzel et al. 2004). And in this work both objects were classified into the S-complex class.

Additionally, geometric albedo values are available for four NEOs. Among them, (12923) Zephyr, (140158) 2001 SX169, and

<sup>1</sup> <https://wiki.helsinki.fi/display/PSR/HG1G2+tools>



**Figure 2.** Colour–colour diagrams showing main taxonomic classes for our data set. The boxes correspond to the  $1\sigma$  deviation from the mean colour values for the group of silicate (blue box) and carbonaceous (red box) objects.

(363599) 2004 FG11 that have moderate albedo compatible with the classification of these objects into S- and X-complexes. Similarly, NEO (363027) 1998 ST27 has a low albedo and is classified into C-complex in this work.

#### 4 DATA ANALYSIS AND DISCUSSION

For the objects in our data set, we calculated the average colours for each taxonomic class and compared them with those reported in the literature. Namely we use colours from DeMeo et al. (2009), that were derived from the spectral data, and colours from Ieva et al. (2018) and Lin et al. (2018), that were obtained from the broad-band photometric observations (see Table 2). We found that the average colours obtained in this work are in general agreement with the literature values. We do not include A- and V-types in Table 2 as we have only a few asteroids classified into these taxons.

For the new data the taxonomic classes are distributed as follows: 20 objects are classified as S-complex, both C- and X-complexes have nine objects, two objects are D-type, and one object is classified as V-type. No objects were classified as A-type. By adding new surface colour data for 42 NEOs, the NEOROCKS data set increased to 93 objects. Considering the results obtained by Hromakina et al. (2021), in the extended sample of 92 objects (2022 GY2 not included), 46 per cent are classified into S-complex, 18 per cent into C-complex,

18 per cent into X-complex, 13 per cent as D-type, 3 per cent as A-type, and 3 per cent as V-type (Fig. 3).

Nearly a half of NEOs in our data set fall into the S-complex. This predominance of silicate S-complex asteroids among NEOs is consistent with existing surveys on NEOs. Such prevalence of S-type asteroids among NEOs can be affected by an observational bias towards objects with higher albedo. Thus, to obtain knowledge about the real compositional distribution, a debiasing technique should be applied. Given that the size of our sample is still relatively small, the debiasing of our data is beyond the scope of this work. We note that in the recent work by Marsset et al. (2022), the authors presented a debiased compositional distribution of NEOs. In particular, the portion of S-complex in their data set drops from 66 to 42 per cent for the bias-corrected distribution, and the amount of primitive C-complex asteroids doubles and goes from about 20 to 40 per cent.

As a significant portion of our data consists of PHAs, we looked for possible differences in the compositional distribution of PHAs and non-PHAs, and found no significant difference in the overall distribution between these two groups. The lack of compositional difference between PHAs and the rest of the NEOs population was also reported by Perna et al. (2016).

For further analysis, we split the classified objects in our data set into groups of silicate objects, that includes S-complex, A-, and V-types, and carbonaceous objects, that consists of C-complex, D-type, and low-albedo X-types (also known as P-types in the Tholen taxonomy (Tholen 1984)). The remaining objects, namely X-complex asteroids with unknown albedo, are put into the miscellaneous group. This resulted in 47 objects in the silicate group, 28 objects in the carbonaceous group, and 17 objects in the miscellaneous group.

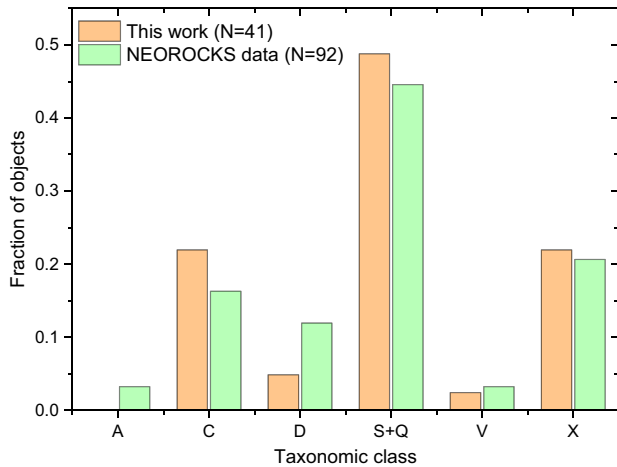
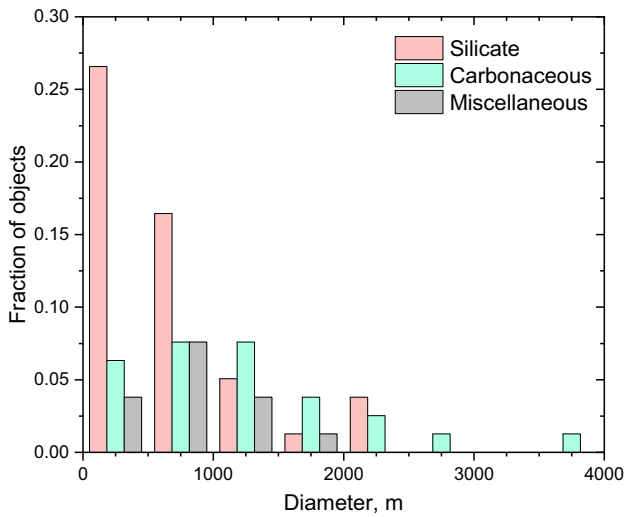
Fig. 4 shows diameter distribution of the silicate, carbonaceous, and miscellaneous objects in the NEOROCKS data set. The estimated sizes of the objects spread out from about 20 m to almost 4 km, with the majority of objects being in the  $D < 1$  km range. The number of carbonaceous objects in our data set steadily decreases with size. Silicate objects are much more prevalent among smaller objects, but its number drops significantly for  $D > 1$  km. The relative ratio of carbonaceous to silicate objects with  $D < 500$  m is 28–72 per cent, and for objects with  $D > 500$  m the ratio is 46 to 54 per cent. Such distribution is most probably caused by the bias towards higher albedo objects.

We looked into the possible differences in the orbital and physical parameters between the different groups of objects analysed in this work. In Table 3, we present the median values of the main orbital elements, absolute magnitude, as well as the estimated diameter for the whole data set, groups of silicate and carbonaceous objects, and also for the PHAs and non-PHAs. The ‘dispersion’ of the median values was calculated as a median absolute deviation (MAD). Carbonaceous objects show slightly higher orbital inclinations and larger estimated diameters compared to the silicate ones. The Earth’s MOID is lower for silicate objects, which in turn also suggests a generally lower MOID for smaller asteroids in our data set because as we already established, the majority of objects with  $D < 500$  m belong to the silicate group. PHAs in the data set, as expected, have smaller  $q$ ,  $Q$ , and  $a$  values, as well as slightly smaller diameters than non-PHAs. Otherwise, we do not find any significant correlations between the orbital and physical parameters for the objects in our data set.

As already mentioned, close approaches of NEOs to the Earth raise a concern due to the possible impact as well as create a possibility to investigate these objects *in situ* by a space mission. In this regard, objects with the smaller Earth’s MOIDs (i.e. PHAs) are better candidates for space mission targets. Another parameter

**Table 2.** Average colours obtained in this work for each taxonomic class in comparison to the literature values from DeMeo et al. (2009), Ieva et al. (2018), and Lin et al. (2018).

| Taxonomic class | $B-R$           | $B-R_{\text{Lin18}}$ | $B-R_{\text{Ieva18}}$ | $B-R_{\text{DeMeo09}}$ | $V-I$           | $V-I_{\text{Lin18}}$ | $V-I_{\text{Ieva18}}$ | $V-I_{\text{DeMeo09}}$ |
|-----------------|-----------------|----------------------|-----------------------|------------------------|-----------------|----------------------|-----------------------|------------------------|
| C               | $1.18 \pm 0.09$ | 1.06                 | $1.07 \pm 0.12$       | $1.09 \pm 0.11$        | $0.69 \pm 0.06$ | 0.67                 | $0.67 \pm 0.07$       | $0.69 \pm 0.10$        |
| D               | $1.18 \pm 0.05$ | 1.19                 | $1.21 \pm 0.06$       | $1.18 \pm 0.07$        | $0.92 \pm 0.08$ | 0.87                 | $0.89 \pm 0.03$       | $0.89 \pm 0.07$        |
| S               | $1.32 \pm 0.07$ | 1.27                 | $1.32 \pm 0.07$       | $1.29 \pm 0.14$        | $0.83 \pm 0.11$ | 0.81                 | $0.77 \pm 0.09$       | $0.82 \pm 0.14$        |
| X               | $1.14 \pm 0.05$ | 1.13                 | $1.19 \pm 0.06$       | $1.13 \pm 0.12$        | $0.80 \pm 0.04$ | 0.79                 | $0.78 \pm 0.05$       | $0.78 \pm 0.06$        |

**Figure 3.** Distribution of the taxonomic classes obtained in this work and the overall distribution for the NEOROCKS survey data.**Figure 4.** Size distribution of 92 NEOs in our data set.

that should be taken into consideration is  $\Delta V$ , which is a measure of the impulse necessary for a spacecraft to reach the orbit of a target. According to Hinkle et al. (2015), with current propulsion technology, only objects with  $\Delta V < 7 \text{ km s}^{-1}$  can be accessed by a spacecraft. Fig. 5 shows the Earth’s MOID and  $\Delta V$  values, that were taken from the MPC website, for the observed objects. In total, 14 objects have both MOID  $< 0.05 \text{ au}$  and  $\Delta V < 7 \text{ km s}^{-1}$  (Table 4). The majority of them (6 out of 10) belong to the silicate group, three objects are from the miscellaneous group and only one is from the carbonaceous group. Of particular interest are D-type and rare A-

type asteroids, because they have not been visited by space missions yet (Barucci et al. 2018). In this regard, we can mention two objects from our data: D-type NEO (163014) 2001 UA5 and A-type NEO 2017 SE19. In Table 4, we also show the values of the parameter  $U$ , which corresponds to the orbit uncertainty, where 0 corresponds to a very small uncertainty and nine indicates a very large uncertainty.

## 5 SUMMARY AND CONCLUSIONS

In this work, we present new observational data for 42 small NEOs obtained within the NEOROCKS project. For these asteroids, we computed surface colours, and estimated their taxonomic class, absolute magnitudes, and diameters. Based on the  $B-V$ ,  $V-R$ , and  $V-I$  surface colours and considering only the main taxonomic classes, most of the observed objects (20 NEOs) were classified into the S-complex, nine as C-complex, nine as X-complex, two as D-type, and one as V-type.

By adding these new observational data, we expanded our data set to 93 objects. The compositional distribution of the updated data set is as follows: most of the objects (46 per cent) were classified into the S-complex, 18 per cent into the X-complex, 18 per cent into C-complex, and 13 per cent as D-type. The remaining small number of objects were classified as A-types (3 per cent) and V-types (3 per cent). The calculated mean colours for the taxonomic classes considered in this work are in agreement with the literature values (DeMeo et al. 2009; Ieva et al. 2018; Lin et al. 2018). PHAs do not show a significant difference in the compositional distribution from the rest of the population.

Asteroids in our data set with sizes  $D < 500 \text{ m}$  predominantly belong to the silicate group. This result is due to the observational bias towards higher albedo objects rather than an intrinsic compositional difference.

The group of silicate objects shows the lower Earth MOID compared to the group of low-albedo carbonaceous objects. Silicate objects also show a slightly smaller median inclination, but more data is needed to confirm a possible difference.

Finally, we selected objects that could be considered as space mission targets based on their MOID and  $\Delta V$  values. Among 10 objects in our data set that satisfy both criteria, we particularly note primitive D-type asteroids (163014) 2001 UA5 and rare A-type asteroid 2017 SE19.

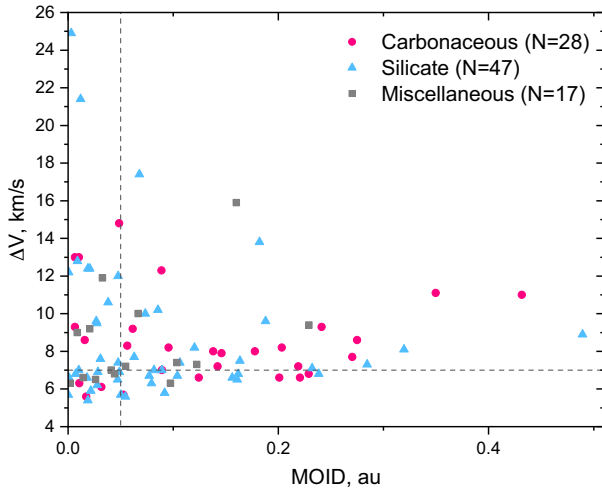
The NEOROCKS project is still ongoing and new observational runs are scheduled. In the final article, which will be done at the end of the project, we will summarize the obtained results on the surface colours of NEOs, and perform a global statistical analysis that will include available literature data.

## ACKNOWLEDGEMENTS

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**Table 3.** Median values of the orbital and physical parameters for the whole data set and different subgroups discussed in this work. The uncertainty value was calculated as median absolute deviation.

| Group                  | $e$             | $i, ^\circ$      | $a$ , au        | $q$ , au        | $Q$ , au        | MOID, au        | $H$              | $D$ , m       |
|------------------------|-----------------|------------------|-----------------|-----------------|-----------------|-----------------|------------------|---------------|
| All data (N = 92)      | $0.49 \pm 0.08$ | $10.38 \pm 6.24$ | $1.78 \pm 0.50$ | $0.94 \pm 0.19$ | $2.74 \pm 0.83$ | $0.06 \pm 0.05$ | $19.00 \pm 1.15$ | $572 \pm 290$ |
| PHAs (N = 36)          | $0.50 \pm 0.09$ | $9.92 \pm 6.61$  | $1.58 \pm 0.50$ | $0.78 \pm 0.18$ | $2.39 \pm 0.89$ | $0.02 \pm 0.01$ | $19.30 \pm 1.10$ | $540 \pm 268$ |
| non-PHAs (N = 56)      | $0.49 \pm 0.06$ | $11.38 \pm 6.50$ | $2.12 \pm 0.49$ | $1.03 \pm 0.15$ | $3.12 \pm 0.83$ | $0.12 \pm 0.06$ | $18.85 \pm 1.15$ | $666 \pm 263$ |
| Silicate (N = 47)      | $0.48 \pm 0.04$ | $11.38 \pm 7.42$ | $1.95 \pm 0.39$ | $0.95 \pm 0.14$ | $2.93 \pm 0.71$ | $0.05 \pm 0.03$ | $19.00 \pm 1.10$ | $495 \pm 305$ |
| Carbonaceous (N = 28)  | $0.50 \pm 0.08$ | $12.35 \pm 6.28$ | $1.65 \pm 0.53$ | $0.92 \pm 0.24$ | $2.50 \pm 0.84$ | $0.09 \pm 0.08$ | $19.00 \pm 1.30$ | $808 \pm 382$ |
| Miscellaneous (N = 17) | $0.54 \pm 0.09$ | $9.79 \pm 4.63$  | $1.69 \pm 0.60$ | $0.97 \pm 0.23$ | $2.71 \pm 1.13$ | $0.05 \pm 0.04$ | $18.7 \pm 1.10$  | $603 \pm 269$ |

**Figure 5.** The Earth's MOID versus  $\Delta V$  value for the NEOs in our data set. Vertical and horizontal dashed lines at MOID = 0.05 au and  $\Delta V = 7 \text{ km s}^{-1}$ , respectively, separate objects that may be suitable as space mission targets.**Table 4.** List of NEOs that could be potential space mission targets based on their low MOID and low  $\Delta V$ .

| Object              | Taxon        | $\Delta V$ , $\text{km s}^{-1}$ | $U^*$ |
|---------------------|--------------|---------------------------------|-------|
| (12923) Zephyr      | S-complex    | 5.9                             | 0     |
| (52768) 1998 OR2    | X-complex    | 6.6                             | 0     |
| (140158) 2001 SX169 | X-complex    | 6.5                             | 0     |
| (332446) 2008 AF4   | X-complex    | 6.3                             | 0     |
| (388945) 2008 TZ3   | Cg/C-complex | 5.6                             | 0     |
| (163014) 2001 UA5   | D-type       | 6.1                             | 0     |
| (613403) 2006 GB    | C-complex    | 6.4                             | 0     |
| 2009 CC3            | S-complex    | 6.9                             | 0     |
| 2010 TV149          | X-complex    | 6.8                             | 0     |
| 2017 SE19           | A-type       | 6.5                             | 0     |
| 2002 TP69           | S-complex    | 5.7                             | 0     |
| 2020 RO6            | S-complex    | 5.4                             | 0     |
| 2020 YQ3            | S-complex    | 6.8                             | 0     |
| 2022 BH3            | S-complex    | 6.6                             | 6     |

Note. \*Orbit uncertainty parameter taken from the MPC website.

870403. The article is based on observations made at Observatoire de Haute Provence (CNRS), France.

## DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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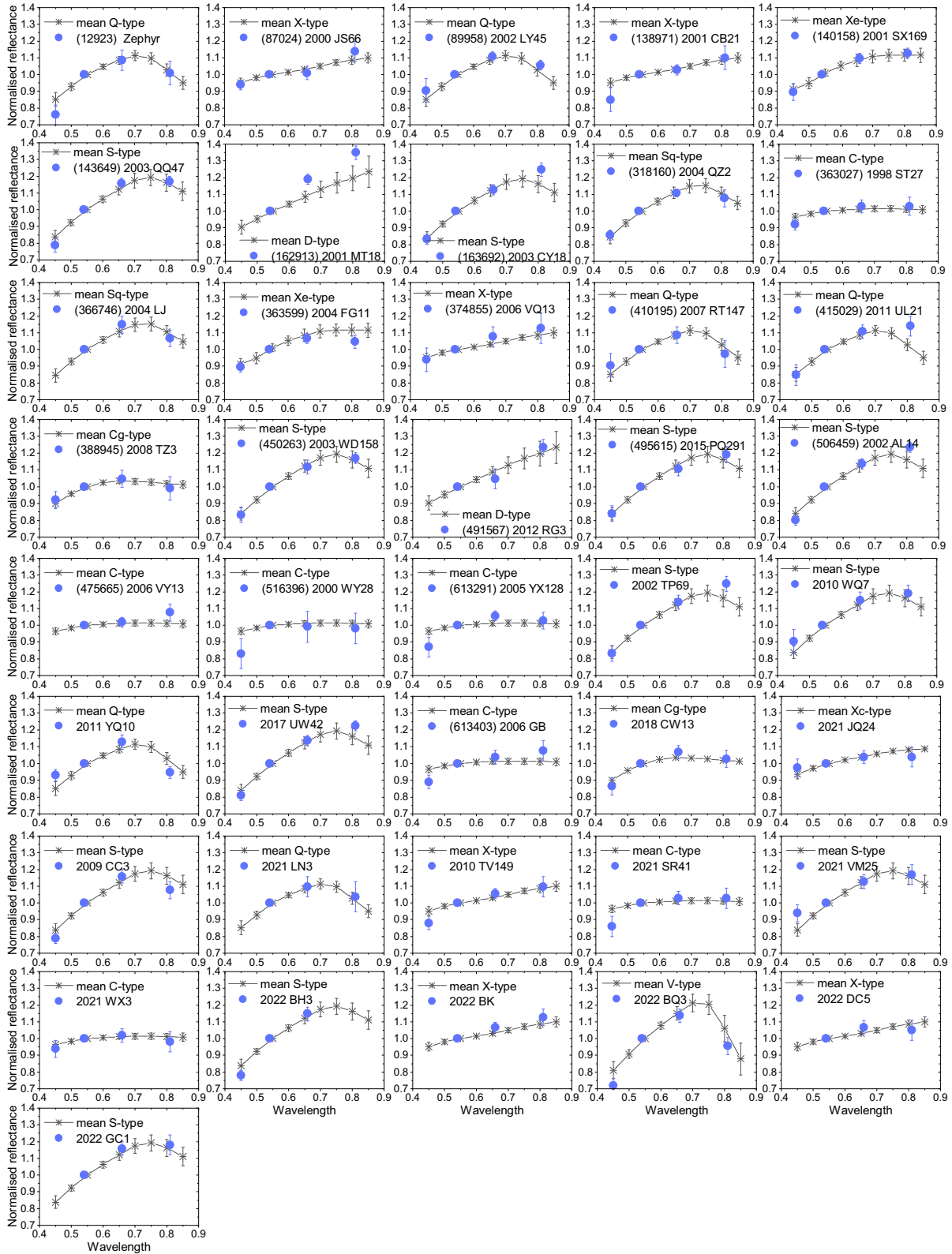
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## APPENDIX A: ORBITAL ELEMENTS OF THE OBSERVED OBJECTS

**Table A1.** List of observed objects and corresponding orbital elements taken from the MPC website.

|    | Object              | Type        | $e$    | $i, ^\circ$ | $a, \text{au}$ | $q, \text{au}$ | Tj    |
|----|---------------------|-------------|--------|-------------|----------------|----------------|-------|
| 1  | (12923) Zephyr      | Apollo, PHA | 0.4922 | 5.305       | 1.9620         | 0.9962         | 3.716 |
| 2  | (87024) 2000 JS66   | Apollo      | 0.1899 | 14.431      | 1.1967         | 0.9694         | 5.260 |
| 3  | (89958) 2002 LY45   | Apollo, PHA | 0.8862 | 9.908       | 1.6417         | 0.1867         | 3.682 |
| 4  | (138971) 2001 CB21  | Apollo, PHA | 0.3333 | 7.899       | 1.0343         | 0.6895         | 5.863 |
| 5  | (140158) 2001 SX169 | Apollo, PHA | 0.4609 | 2.518       | 1.3472         | 0.7262         | 4.764 |
| 6  | (143649) 2003 QQ47  | Apollo, PHA | 0.1870 | 62.102      | 1.0850         | 0.8820         | 5.214 |
| 7  | (162913) 2001 MT18  | Apollo      | 0.5196 | 8.647       | 1.2709         | 0.6105         | 4.929 |
| 8  | (163692) 2003 CY18  | Apollo      | 0.4106 | 7.199       | 1.5266         | 0.8998         | 4.389 |
| 9  | (318160) 2004 QZ2   | Amor        | 0.4929 | 0.9691      | 2.261          | 1.1465         | 3.448 |
| 9  | (363027) 1998 ST27  | Aten, PHA   | 0.5300 | 21.062      | 0.8190         | 0.3850         | 6.978 |
| 10 | (363599) 2004 FG11  | Apollo, PHA | 0.7238 | 3.1269      | 1.5872         | 0.4384         | 4.039 |
| 12 | (366746) 2004 LJ    | Apollo, PHA | 0.4616 | 18.282      | 1.0865         | 0.5850         | 5.559 |
| 13 | (388945) 2008 TZ3   | Apollo, PHA | 0.3907 | 8.7176      | 1.5900         | 0.9689         | 4.278 |
| 14 | (374855) 2006 VQ13  | Apollo, PHA | 0.4457 | 16.698      | 1.0993         | 0.6093         | 5.521 |
| 15 | (410195) 2007 RT147 | Amor        | 0.4668 | 3.831       | 2.2912         | 1.2216         | 3.442 |
| 16 | (415029) 2011 UL21  | Apollo, PHA | 0.6528 | 34.851      | 2.1228         | 0.7369         | 3.245 |
| 17 | (450263) 2003 WD158 | Apollo, PHA | 0.4091 | 16.726      | 1.4264         | 0.8428         | 4.563 |
| 18 | (475665) 2006 VY13  | Amor        | 0.6137 | 4.673       | 4.6727         | 4.6727         | 2.960 |
| 19 | (491567) 2012 RG3   | Apollo      | 0.5286 | 15.918      | 1.5744         | 0.7422         | 4.203 |
| 20 | (495615) 2015 PQ291 | Aten        | 0.2374 | 34.602      | 0.9825         | 0.7493         | 5.991 |
| 21 | (506459) 2002 AL14  | Apollo      | 0.1261 | 22.998      | 1.0376         | 0.9067         | 5.830 |
| 22 | (516396) 2000 WY28  | Amor        | 0.2894 | 19.447      | 1.6384         | 1.1642         | 4.189 |
| 23 | (613291) 2005 YX128 | Apollo      | 0.7347 | 4.476       | 2.1744         | 0.5767         | 3.267 |
| 24 | (613403) 2006 GB    | Aten, PHA   | 0.1793 | 10.061      | 0.9590         | 0.7871         | 6.257 |
| 25 | 2002 TP69           | Amor        | 0.4695 | 1.974       | 1.9475         | 1.0331         | 3.751 |
| 26 | 2009 CC3            | Amor, PHA   | 0.5373 | 11.372      | 2.2006         | 1.0182         | 3.440 |
| 27 | 2010 TV149          | Apollo, PHA | 0.5188 | 9.792       | 1.6989         | 9.7926         | 4.025 |
| 28 | 2010 WQ7            | Amor        | 0.5567 | 13.610      | 2.3699         | 1.0504         | 3.285 |
| 29 | 2011 YQ10           | Amor        | 0.5216 | 2.397       | 2.2418         | 1.0724         | 3.440 |
| 30 | 2017 UW42           | Amor        | 0.4842 | 6.670       | 2.4560         | 1.2667         | 3.313 |
| 31 | 2018 CW13           | Apollo      | 0.7051 | 28.918      | 1.6108         | 0.4750         | 3.921 |
| 32 | 2021 JQ24           | Amor        | 0.6695 | 5.993       | 3.2256         | 1.0659         | 2.776 |
| 33 | 2021 LN3            | Apollo      | 0.5662 | 28.80       | 2.2776         | 0.9881         | 3.241 |
| 34 | 2021 SR41           | Apollo      | 0.6502 | 21.935      | 2.3796         | 0.8324         | 3.140 |
| 35 | 2021 VM25           | Apollo      | 0.3913 | 9.162       | 1.6474         | 1.0028         | 4.181 |
| 36 | 2021 WX3            | Amor        | 0.5144 | 7.853       | 2.1988         | 1.0677         | 3.471 |
| 37 | 2022 BH3            | Apollo      | 0.5972 | 3.943       | 2.1629         | 0.8711         | 3.437 |
| 38 | 2022 BQ3            | Amor        | 0.6027 | 15.088      | 2.8279         | 1.1237         | 2.976 |
| 39 | 2022 BK             | Amor        | 0.5801 | 10.713      | 2.4666         | 1.0357         | 3.212 |
| 40 | 2022 DC5            | Apollo      | 0.2061 | 3.925       | 1.0142         | 0.8052         | 2.976 |
| 41 | 2022 GC1            | Apollo      | 0.4006 | 13.331      | 1.1695         | 0.7009         | 5.294 |
| 42 | 2022 GY2            | Apollo, PHA | 0.8647 | 6.199       | 2.1673         | 0.2933         | 3.049 |

## APPENDIX B: INDIVIDUAL REFLECTANCE SPECTRA OF THE TARGETS



**Figure B1.** Individual reflectance spectra of the objects observed in this work (blue dots) together with the mean spectra of the most fitting taxonomic class from DeMeo et al. (2009) (black asterisks). The spectra are normalized at  $0.54 \mu\text{m}$ .

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