Lightcurves and Rotations of Trans-Neptunian Objects in the 2:1 Mean Motion Resonance with Neptune

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ABSTRACT

We report the rotational lightcurves of 21 trans-Neptunian objects (TNOs) in Neptune’s 2:1 mean motion resonance obtained with the 6.5 m \textit{Magellan-Baade telescope} and the 4.3 m \textit{Lowell Discovery Telescope}. The main survey’s goal is to find objects displaying a large lightcurve amplitude which is indicative of contact binaries or highly elongated objects. In our sample, two 2:1 resonant TNOs showed a significant short-term lightcurve amplitude: 2002 VD\textsubscript{130} and (531074) 2012 DX\textsubscript{98}. The full lightcurve of 2012 DX\textsubscript{98} infers a periodicity of 20.80±0.06 h and amplitude of 0.56±0.03 mag whereas 2002 VD\textsubscript{130} rotates in 9.85±0.07 h with a 0.31±0.04 mag lightcurve amplitude. Based on lightcurve morphology, we classify (531074) 2012 DX\textsubscript{98} as a likely contact binary, but 2002 VD\textsubscript{130} as a likely single elongated object. Based on our sample and the lightcurves reported in the literature, we estimate the lower percentage of nearly equal-sized contact binaries at only 7-14 \% in the 2:1 resonance, which is comparable to the low fraction reported for the dynamically Cold Classical trans-Neptunian objects. This low contact binary fraction in the 2:1 Neptune resonance is consistent with the lower estimate of the recent numerical modeling. We report the Sloan g', r', i' surface colors of 2002 VD\textsubscript{130} which is an ultra-red TNO whereas 2012 DX\textsubscript{98} is a very red object based on published surface colors.

Keywords: Trans-Neptunian objects (1705), Resonant Kuiper belt objects (1396), Twotinos (1727)

1. INTRODUCTION

Located at about 47.7 AU, the 2:1 mean motion resonance with Neptune is the second known most populated resonance after Neptune’s 3:2 mean motion resonance at ∼39.4 AU (Volk et al. 2016; Bannister et al. 2018; Chen et al. 2019). The 2:1 Neptune resonance is just beyond the main classical Kuiper Belt and is likely made up of objects that formed in the main classical belt as well as objects scattered outward from the giant planet region before being trapped into the resonance (Sheppard 2012). The dynamically classical population\textsuperscript{1} is trapped between the 3:2 and 2:1 resonances and is generally divided between the dynamically Hot and Cold classical. Typically, the Cold classicals have an inclination \(i\leq4-5\degree\), but some works infer that the inclination threshold should be at about 12\degree (Brown 2001; Elliot et al. 2005; Peixinho et al. 2008; Gladman et al. 2008). Also, Petit et al. (2011) suggested that the Cold Classical population is composed of at least two sub-groups, the stirred and the kernel.

As of February 2022, the Deep Ecliptic Survey\textsuperscript{2} has classified 106 trans-Neptunian objects (TNOs) confined in the 2:1 resonance. Some objects are classified as likely 2:1 TNOs but some other classifications (e.g., Centaur or Scattered Disk Object) are also possible based

\textsuperscript{1}For the purpose of this work, our definition of the Cold Classical population is the same as in Thirouin & Sheppard (2019a).

\textsuperscript{2}The Deep Ecliptic Survey (DES) object classification is available at https://www.boulder.swri.edu/~buie/kbo/desclass.html
on the currently available astrometry. These objects are 2006 SG\textsubscript{415}\textsuperscript{3}, 2009 MG\textsubscript{10}, 2013 TD\textsubscript{228}, 2014 SX\textsubscript{349}, 2014 YZ\textsubscript{91}, (554102) 2012 KW\textsubscript{51}, 2016 SJ\textsubscript{56}, 2017 FD\textsubscript{163}, and 2017 FQ\textsubscript{161}.

For decades, lightcurves have been used to estimate the rotational period and the lightcurve amplitude, as well as to derive the rotational properties (shape, binarity, surface features, and others) of small bodies across the Solar System (e.g., Pravec & Harris (2000); Sheppard et al. (2008); Thirouin et al. (2016); Thirouin & Sheppard (2019a)). Most TNO lightcurve surveys use small 1 to 2 m class telescopes and thus are limited to bright objects with, typically, a visual magnitude (V) brighter than \(\sim 21\) mag (Thirouin et al. 2010; Sheppard et al. 2008). Therefore, there is a bias in the literature toward brighter and thus larger objects, which skews our current understanding of the rotational properties of the TNOs as a population. Recently, several surveys dedicated to the rotational lightcurves of small TNOs were designed using 4 to 8 m class telescopes to observe TNOs as faint as V \(\sim 25\) mag (Alexandersen et al. 2019; Thirouin & Sheppard 2019a, 2018). These new surveys aim to improve our overall understanding of the TNO rotational properties by pushing the facilities to their limit of detectability, but more work has to be done. Observing fainter objects is required, but it is also necessary to increase the number of objects with rotational lightcurves in most of the TNO sub-populations.

Little is known about the rotational characteristics of the 2:1 resonant TNOs. Only four objects (see Section 4.1 for more details) – (26308) 1998 SM\textsubscript{165}, (119979) 2002 WC\textsubscript{19}, (469505) 2003 FE\textsubscript{128}, and (312645) 2010 EP\textsubscript{65} – have published rotational lightcurve studies (Romanishin et al. 2001; Sheppard & Jewitt 2002; Kern 2006; Spencer et al. 2006; Sheppard 2007; Benecchi & Sheppard 2013; Thirouin 2013). Three of them have resolved companions while 2010 EP\textsubscript{65} is the only one with no satellite detected based on Hubble Space Telescope images. The satellites of 1998 SM\textsubscript{165}, 2002 WC\textsubscript{19}, and 2003 FE\textsubscript{128} were discovered after their lightcurve studies. Because the lightcurve sample of 2:1 resonant TNOs is extremely limited, biased towards resolved binary systems, and biased towards bright objects, we aim for this paper to observe faint single 2:1 resonant objects to improve our understanding of this sub-population. Below, we will describe our survey strategy and target selection. We will also summarize the rotational properties of the 2:1 TNOs and estimate the contact binary percentage in this resonance.

2. SURVEY DESCRIPTION AND FACILITIES

Our 2:1 Neptune resonance lightcurve survey strategy is inspired by the dynamically Cold Classical survey published in Thirouin & Sheppard (2019a). The strategy is to image a substantial set of TNOs for partial lightcurves to constrain their rotational periods and amplitudes as well as to discover interesting objects with a large amplitude (typically, larger than 0.4 mag) which can be indicative of contact binaries or highly elongated objects.

Our first target selection criterion is the visual magnitude. Bright objects (V \(\lesssim 22\) mag) are already covered by the literature and because we are using 4 and 6 m class telescopes, we select objects with a V between \(\sim 22\) and 23.5-24 mag (more details about facilities below). Preferentially, TNOs without a known resolved companion are chosen, but several of our targets have never been observed with Hubble Space Telescope thus their resolved binarity status is unknown (see Table 1). Targets are also selected to cover a large range of eccentricities and inclinations (semi-major axis is also considered but the range is limited due to the definition of the 2:1 resonant population), as well as absolute magnitudes (i.e., sizes). Our selected targets are plotted in Figure 1.

Our survey makes use of two facilities. The Magellan-Baade telescope at Las Campanas observatory is equipped with IMACS which is a wide-field imager with 8 CCDs giving a 27.4′ diameter field and a pixel scale of 0.20′/pixel. Our runs at the Lowell Discovery Telescope (LDT), formerly known as Lowell’s Discovery Channel Telescope (DCT), uses the Large Monolithic Imager which is a 6144\times6160 pixels CCD with a field of view of 12.5′\times12.5′ and a pixel scale of 0.12″/pixel. Exposure times range from 200 to 600 s and are adjusted based on the weather conditions and the facility. All observations are obtained with a broad-band filters (VR and WB4800-7800 filters at LDT and Magellan-Baade, respectively) to maximize the target’s signal-to-noise ratio. In one instance, we used the Sloan g’r’i’ filters for surface color determination.

All images are calibrated with bias and dome or twilight flats before proceeding with aperture photometry. Once the photometry is on hand, we search for periodicity using the Lomb and the Phase Dispersion Minimization (PDM) techniques (Lomb 1976; Stellingwerf 1978). This series of steps is standard and has been already described in greater detail in Thirouin et al. (2010).

\textsuperscript{3} The partial lightcurve of 2006 SG\textsubscript{415} is presented in this paper. Based on the DES classification, 2006 SG\textsubscript{415} is likely a 2:1 resonant TNO, but it can also be a Scattered Disk Object (SDO). Therefore, care will be taken to include or exclude this object during the presentation and discussion of our results.
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3. FROM FLAT TO LARGE AMPLITUDE LIGHTCURVES

3.1. What is a lightcurve?

A lightcurve (i.e. brightness variation as a function of time) of a small body is determined by the periodic variation of the body brightness due to its rotation. The two main parameters derived from a lightcurve are: (1) the time separation of repeated brightness peaks in the lightcurve gives the object’s rotational period (P) and (2) the full (or peak-to-peak) lightcurve amplitude (\(\Delta m\)). Rotational period, lightcurve amplitude, and lightcurve morphology can be used to infer some physical and rotational properties of the body: shape, surface heterogeneity/homogeneity, internal structure, density, and binarity (Sheppard et al. 2008). A lightcurve is due to (1) albedo variation(s) on the object surface, (2) non-spherical shape, and/or (3) binarity (Sheppard et al. 2008). Assuming hydrostatic equilibrium, a small body with a spherical shape is called MacLaurin spheroid whereas an elongated triaxial ellipsoidal object is a Jacobi object (Chandrasekhar 1969). As illustrated in Thirouin et al. (2014), a MacLaurin object will have a single-peaked lightcurve whereas a Jacobi or contact binary will display a double-peaked lightcurve. Typically, a spheroidal body with albedo spot(s) on its surface will have a low amplitude lightcurve such as \(\Delta m\lesssim 0.15\) mag. A triaxial ellipsoidal object will have a sinusoidal lightcurve with a moderate lightcurve amplitude of \(\sim 0.15\) mag. The lightcurve of a nearly equal-sized contact binary observed equator-on will have a \(\Delta m\geq 0.9\) mag and the maximum/minimum of brightness is an inverted U-shape/V-shape from shading effects (Lacerda & Jewitt 2007; Lacerda 2011; Lacerda et al. 2014; Harris & Warner 2020). If a contact binary is imaged when the line of sight is further off the equator, the lightcurve will have lower amplitude, and the V-/U-shapes will be less prominent (Lacerda 2011). Therefore, Thirouin & Sheppard (2019a) uses: an object with an amplitude greater than 0.9 mag, and the V-/U-shapes is a confirmed contact binary but a likely contact binary will have large amplitude except that under a 0.9 mag cutoff and the U-/V-shapes are less prominent (Descamps 2015; Lacerda 2011; Leone et al. 1984). Following Thirouin & Sheppard (2019a), for an object with \(\Delta m>0.4\) mag, we will discuss if it is a likely contact binary or a single triaxial object. We note that ideally two lightcurves obtained at significantly different epochs are needed for lightcurve modeling purposes to confirm the morphology of the object/system (Lacerda et al. 2014; Lacerda 2011).

Figure 1. The 2:1 resonant TNOs are classified into 4 groups: (1) objects with a lightcurve from the literature (blue squares, see Section 4.1 for more details), (2) objects with a flat to moderate lightcurve amplitude from our survey (green triangles), (3) objects with a large lightcurve amplitude from this survey (red diamond), and (4) objects never observed for lightcurve study (black circles). Our survey is combined with published lightcurves of 2:1 TNOs to cover a range of inclination, eccentricity and absolute magnitude. Notes: The nine likely 2:1 TNOs mentioned in the Introduction are plotted. Orbital elements, absolute and visual magnitudes are from the Minor Planet Center (February 2022).
Following, we classify the 21 confirmed 2:1 resonant TNOs (plus 2006 SG415) lightcurves obtained for this work in categories based on their amplitude: (1) a flat lightcurve displays no significant variability, (2) a low amplitude lightcurve has a $\Delta m<0.2$ mag, (3) a moderate amplitude lightcurve with $0.2$ mag $<\Delta m<0.4$ mag, and (4) a large amplitude lightcurve with $\Delta m>0.4$ mag.

### 3.2. Large Amplitude Lightcurves

2002 VD$_{130}$—This object was observed on several occasions with the LDT from 2019 to 2021 (Figure 2). The Lomb periodogram inferred a rotational period of 4.87 cycles/day (or 4.93 h), but there are several nearby aliases with a high confidence level as well. Due to the large amplitude and asymmetric lightcurve with the first minimum being deeper than the second one, the double-peaked rotational period is favored. The rotational period of 2002 VD$_{130}$ is about $9.85\pm0.07$ h and the full lightcurve amplitude is $0.31\pm0.04$ mag from the second-order Fourier fit. The lightcurve of 2002 VD$_{130}$ displays a large amplitude, but there is no sign of the characteristics V-shape and U-shape of a contact binary. The sinusoidal morphology of this lightcurve would currently suggest that 2002 VD$_{130}$ is an elongated object and not a clear contact binary candidate. Future observations at a significantly later epoch will help determine the true nature of this object, but for now, we do not classify 2002 VD$_{130}$ as a candidate contact binary TNO.

Following the formalism described in Chandrasekhar (1987), one can derive the axis ratio and lower limit to the density of an ellipsoidal object in hydrostatic equilibrium for a given rotational period. If 2002 VD$_{130}$ is an elongated Jacobi body with axes such as $a>b>c$ and is rotating along its c-axis, its density is $\rho \geq 0.42$ g cm$^{-3}$ and the axis ratios are $a/b=1.46$, and $c/a=0.47$ assuming that this object was observed under an equatorial view. If we consider that the lightcurve of 2002 VD$_{130}$ is single-peaked, then its rotational period is 4.93 h (half the period of the double-peaked lightcurve), and in this case, the lower limit to the density would be $1.69$ g cm$^{-3}$. Grundy et al. (2012) reported the densities of several binary/multiple systems which were extracted from their mutual orbitals and mass determinations. Based on Figure 7 in Grundy et al. (2012), there is a clear trend inferring that small objects have density lower than 1 g cm$^{-3}$ whereas the large objects have densities above 1 g cm$^{-3}$ limit. 2002 VD$_{130}$ has a diameter between $\sim100$ and $\sim200$ km (assuming an albedo of 0.20 or 0.04, respectively), therefore its density is likely below or around 1 g cm$^{-3}$. Therefore, we can rule out the density estimate derived from the single-peaked lightcurve, and also clearly favor the double-peaked lightcurve.

(531074) 2012 DX$_{98}$—This object was observed seven times with the Magellan-Baade telescope and during one night with the LDT between May 2018 and March 2019. The Lomb periodogram in Figure 3 favored a single-peaked period of 2.31 cycles/day (i.e., 10.40 h), but the double-peaked rotational period of 20.80 h, and amplitude of 0.56 mag is preferred (Figure 3). The lightcurve morphology with the V- and U-shapes is characteristic of a contact binary from the shadowing effects of the two components. However, the lightcurve amplitude is below the threshold generally used to classify an object as a nearly equal-sized contact binary (Sheppard & Jewitt)

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4 Photometry and partial/flat lightcurves are available in Appendix A and Appendix B.
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So, following the terminology used in Thirouin & Sheppard (2019a), we consider 2012 DX$_{98}$ as a likely contact binary as future observations will determine if the amplitude gets larger as the object becomes more viewed equator-on.

If 2012 DX$_{98}$ is a contact binary, its mass ratio is between $q_{\text{max}}=0.53$ with $\rho_{\text{max}}=5$ g cm$^{-3}$ and $q_{\text{min}}=0.47$ with $\rho_{\text{min}}=1$ g cm$^{-3}$. Because $q_{\text{min}}$ and $q_{\text{max}}$ are comparable, we consider the case where $q=0.5$ and $\rho=1$ g cm$^{-3}$ to estimate that the axis ratios for the primary are $b_p/a_p=0.97$, $c_p/a_p=0.94$, and for the secondary $b_s/a_s=0.93$, $c_s/a_s=0.91$, while the separation between the two components is $D=0.48$ corresponding 252/113 km (with an albedo of 0.04/0.20).

Even if the contact binary configuration is favored, we also consider the case of a single elongated object to estimate that the density should be larger than 0.10 g cm$^{-3}$ for a body with $a/b=1.67$ and $c/a=0.43$ (Chandrasekhar 1987).

3.3. Moderate Amplitude Lightcurves

2004 HP$_{79}$—In about 3 h of observations, 2004 HP$_{79}$ has a variability of 0.29 mag. We do not have enough data to derive a rotational period.

(470082) 2006 SC$_{309}$—This object was observed over two non-consecutive nights in October 2019 over 4.5 h and 5 h, respectively. The variability is not consistent over the two observing blocks as we reported a variability of 0.38 mag and 0.08 mag. After a detailed inspection of our dataset, there is no obvious background contamination able to explain such different amplitudes. Therefore, we considered that both runs tested different phases of the lightcurve, possibly indicating a very long period for this object. For the following statistical analysis, we will use a mean amplitude of 0.23 mag.

(55025) 2014 WT$_{509}$—Based on one isolated night at the Magellan telescope, we report a moderate lightcurve amplitude of 0.26 mag over 5 h of observations. We re-observed this object at the LDT, but the weather, as well as technical difficulties, resulted in low-quality data. Therefore, for our study, we will only consider the results from the Magellan-Baade lightcurve.

3.4. Flat and Low Amplitude Lightcurves

(137295) 1999 RB$_{216}$—In about 6 h, this object presents an amplitude of $\sim$0.12 mag. We imaged a minimum and part of the maximum in one night, therefore we constrain the rotational period to be about 6/12 h assuming a single-/double-peaked option.

Figure 3. The main peak favored by the Lomb periodogram is at 2.31 cycles/day (10.40 h). Due to the large amplitude and assymetric lightcurve, we choose the double-peaked period of $2 \times 10.40$ h =20.80 h.

2000 QL$_{251}$—This object is the only known resolved binary observed during our survey. The variability is low, about 0.15 mag over 6 h.

(524179) 2001 FQ$_{185}$—We report a consecutive maximum and minimum during our observations allowing us to constrain the rotational period to $\sim$6.8 h while the amplitude is $\sim$0.06 mag.

2001 UP$_{18}$—Based on about 5 h of observations under variable weather conditions, we report an amplitude likely lower than or near 0.2 mag for this object.

2003 UP$_{292}$—We only have a few images for the above reasons, and can only conclude that the object’s variability was low over about 1 h.

2012 KW$_{51}$—In approximately 5 h, 2012 KW$_{51}$ displayed a variability of $\sim$0.12 mag.
2013 GW_{136} — This body was observed over 2 consecutive images at the LDT. Because we only obtained 2 usable images on the second night, the period and amplitude constraints are based on the first night. The period of 2013 GW_{136} is longer than 4 h and the amplitude is likely greater than 0.17 mag.

2014 GE_{554} — Based on ~4 h of observations with the Magellan-Baade telescope over one night, 2014 GE_{554} variability is only ~0.1 mag. This dataset alone is insufficient to derive the periodicity of this object.

(534626) 2014 UT_{224} — In three isolated nights, we observed this object under variable conditions, and thus we only report a handful of images suggesting an amplitude larger than 0.1 mag over 3.5 h.

2017 DN_{121} — With only one night of data for 2017 DN_{121}, we can only infer that the variability of this object is low, around 0.1 mag in 5 h.

2002 PU_{170}, 2004 TV_{357}, 2006 SG_{415}, 2011 EY_{90}, 2012 WE_{57}, 2012 XR_{157}, and 2013 TG_{172} — The objects 2002 PU_{170}, 2006 SG_{415}, 2011 EY_{90}, 2012 WE_{57}, 2012 XR_{157} and 2013 TG_{172} were observed over one or two observing nights and they all displayed a very low variability. The only known 2:1 resonant TNO with neutral surface colors according to Sheppard (2012), 2004 TV_{357}, was scheduled for observations over 3 non-consecutive nights with the LDT in 2019 and 2020. Over this amount of time, the lightcurve amplitude was very low.

Table 1. Observing log with the date of observations (UT-obs), number of images (N), heliocentric and geocentric distances (r_h and \( \Delta \)), and phase angle (\( \alpha \)) for our runs. The last column presents any hints for resolved wide binary based on Hubble Space Telescope (HST) observations:

1. objects with a satellite detected are indicated with a yes,
2. objects with no detected moon with a no,
3. a ? means that an object has not been observed with the HST and thus we do not know if they have a resolved companion.

We also summarize our results regarding rotational period and lightcurve amplitude.

| TNO          | UT-obs      | N  | r_h  | \( \Delta \) | \( \alpha \) | Filter | Telescope | Period | Amplitude |
|--------------|-------------|----|------|-------------|-------------|--------|-----------|--------|------------|
| (137295) 1999 RB_{216} | 09/20/2020 | 9  | 33.091 | 33.851 | 1.1 | VR | LDT | >6 | >0.15 |
| 2000 QL_{251} | 10/06/2019 | 8  | 39.782 | 40.773 | 0.2 | VR | LDT | >6 | >0.15 |
| (524179) 2001 FQ_{185} | 05/16/2018 | 9  | 37.002 | 36.033 | 0.5 | WB | Magellan | ~6.8 | ~0.06 |
| 2001 UP_{18} | 09/24/2020 | 10 | 50.198 | 51.011 | 0.7 | VR | LDT | >5 | >0.2 |
|              | 10/17/2020 | 7  | 50.056 | 51.027 | 0.3 | VR | LDT | ... | ...   |
| 2002 PU_{170} | 09/20/2020 | 7  | 42.469 | 43.460 | 0.2 | VR | LDT | ... | ~0.1 |
| 2002 VD_{130} | 12/19/2019 | 8  | 31.461 | 32.419 | 0.4 | VR | LDT | 9.85 | 0.31±0.04 |
|              | 02/02/2020 | 6  | 31.602 | 32.424 | 1.0 | VR | LDT | ... | ...   |
|              | 09/20/2020 | 6  | 32.704 | 32.454 | 1.7 | gri, VR | LDT | ... | ...   |
|              | 12/22/2020 | 19 | 31.505 | 32.468 | 0.4 | VR | LDT | ... | ...   |
|              | 01/18/2021 | 12 | 31.530 | 32.472 | 0.5 | VR | LDT | ... | ...   |
| 2003 UP_{292} | 12/06/2019 | 3  | 27.936 | 28.900 | 0.4 | VR | LDT | >1 | >0.1 |
|              | 12/19/2019 | 4  | 27.949 | 28.907 | 0.4 | VR | LDT | ... | ...   |
| 2004 HP_{29}  | 05/22/2018 | 5  | 38.877 | 37.884 | 0.3 | VR | LDT | >3 | >0.29 |
|              | 05/20/2020 | 5  | 37.852 | 38.858 | 0.2 | VR | LDT | ... | ...   |
| 2004 TV_{357} | 10/03/2019 | 6  | 34.397 | 34.806 | 1.5 | VR | LDT | ... | ~0.1 |
|              | 10/06/2019 | 7  | 34.351 | 34.805 | 1.5 | VR | LDT | ... | ...   |
|              | 02/14/2020 | 5  | 34.441 | 34.779 | 1.5 | VR | LDT | ... | ...   |
| (470063) 2006 SG_{169} | 10/03/2019 | 9  | 30.802 | 31.375 | 1.5 | VR | LDT | >4.5 | >0.38 |
|              | 10/06/2019 | 7  | 30.763 | 31.375 | 1.5 | VR | LDT | >5 | >0.08 |
| 2011 EY_{90}  | 05/20/2020 | 5  | 35.315 | 36.143 | 0.9 | VR | LDT | ... | ~0.1 |
| (531074) 2012 DX_{38} | 05/16/2018 | 8  | 35.119 | 34.306 | 1.0 | WB | Magellan | 20.80 | 0.56±0.03 |
|              | 05/17/2018 | 5  | 35.119 | 34.316 | 1.0 | WB | Magellan | ... | ...   |
|              | 05/18/2018 | 10 | 35.119 | 34.327 | 1.0 | WB | Magellan | ... | ...   |
|              | 05/19/2018 | 11 | 35.119 | 34.337 | 1.1 | WB | Magellan | ... | ...   |

Table 1 continued
4. ROTATIONAL PROPERTIES

4.1. Lightcurves from the literature

Only four bright 2:1 resonant TNOs have significant time-resolved photometric information in the literature (Table 2 and Figure 1). Three of them are known resolved binary systems, and thus the published lightcurves are the system’s lightcurves because the components are unresolvable with ground-based observations.

Sheppard (2007) observed 2002 WC19 over 3 nights in December 2003 with observing blocks of about 6 h, 3 h, and 5.5 h and reported a nearly flat lightcurve. Based on data obtained over three nights in January 2004, Thirouin (2013) also concluded that 2002 WC19 has a nearly flat lightcurve with an amplitude less than 0.10 mag. Benech & Sheppard (2013) reported several potential rotational periods for 2010 EP65 but it seems that the best fit is obtained for a double-peaked lightcurve with a rotational period of 14.97 h and an amplitude of 0.17 mag. Kern (2006) presented 18 images obtained over one observing night of 2003 FE128. A single-peaked lightcurve with a rotational period of 5.85 h and amplitude of 0.50 mag was derived. Unfortunately, less than half of the single-peaked lightcurve was covered during the observing time. Based on Figure 20 of Kern (2006), the amplitude of the dataset is only about 0.25 mag as that is the maximum amplitude actually observed. The 0.50 mag inferred by Kern (2006) is based on the lightcurve fit but as the maximum of the curve is missing it is unclear if the fit is realistic. We use an amplitude of 0.25 mag for this object. Also, because of the moderate to potentially large amplitude the double-peaked lightcurve is maybe a better option compared to the single-peaked one (Thirouin et al. 2014). For this work, we used the double-peaked lightcurve with a period of 11.70 h. Additional data to confirm the amplitude and secure the rotational period are warranted. Several lightcurves of 1998 SM165 have been published. The first lightcurve was obtained by Romanishin et al. (2001) and they favored a period of 7.966 h and amplitude of 0.56 mag based on four nights of data in 1999 and 2000. However, Spencer et al. (2006) inferred a period of 8.40 h using 3 nights from

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The table showing the rotational properties of various TNOs is not transcribed here, as it is formatted in a way that is not easily readable in plain text. However, it includes data such as UT-obs, N, r_k, Δ, α, Filter, Telescope, Period, Amplitude, Hmag, a, e, i, and Binary for each TNO. The table is continued, and the entries include dates, magnitudes, and other relevant data for each observation.
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December 2005. The amplitude is consistent with Romanishin et al. (2001) result and a period of 8.40 h appears to adequately fit the Romanishin et al. (2001) and the Spencer et al. (2006) datasets (J. Spencer, private communication). Sheppard & Jewitt (2002) obtained a partial lightcurve suggesting an amplitude of at least 0.45 mag and a period of at least 7.1 h. Here, we will use the period and amplitude estimated by Spencer et al. (2006).

Finally, several similarities between 1998 SM165 and 2006 SG369 are highlighted. Both objects have similar orbital elements and they might both display large lightcurve amplitudes (see this Section and Section 3). Also, they have similar surface colors with $g'-r'=0.91 \pm 0.04$ mag and $g'-i'=1.31 \pm 0.03$ mag for 2006 SG369 according to Sheppard (2012) and the colors of 1998 SM165 are $g'-r'=0.90 \pm 0.05$ mag and $g'-i'=1.34 \pm 0.07$ mag from Delsanti et al. (2001). Such similar orbital elements and surface colors may indicate that these objects are a pair (Vokrouhlický & Nesvorný 2008; Abedin et al. 2021). Numerical modeling is warranted to confirm such a find.

4.2. Lightcurves from our survey

Our survey observed twenty-one 2:1 resonant TNOs (22 TNOs if 2006 SG415 is included). The TNO 2000 QL251 is a binary system (Noll et al. 2006), but the satellite is not resolved in our images and thus we report the combined lightcurve of the primary and secondary. Four TNOs were observed with HST and have no detected moon: 2001 FQ185, 2002 VD130, 2004 TV357 and 2006 SG369. The other TNOs have never been observed for binarity using HST and so their binarity status is unclear.

Most of the lightcurves reported in this work are partial as our main goal is to identify high amplitude lightcurves and thus potential contact binaries for future more intensive observations. Only the lightcurve of 2001 FQ185 is nearly complete as this object has a rotational period consistent with the observing time spent on this object. Our survey found one likely contact binary, 2012 DX98, and one single elongated object, 2002 VD130.

4.3. Amplitude and period distributions

The literature and our survey report 6 full lightcurves, 12 partial lightcurves, and 7 flat lightcurves (excluding the flat lightcurve of 2006 SG415). Two 2:1 TNOs have the large amplitudes, the likely contact binary 2012 DX98 and the known resolved binary 1998 SM165 (Figure 4). The average amplitude is 0.32 mag for the full lightcurves and 0.16 mag for the partial lightcurves.

Table 2. Published lightcurves of four 2:1 resonant TNOs with information regarding rotational period, lightcurve amplitude and absolute magnitude are summarized.

| Object          | Single-peaked | Double-peaked | $\Delta m$ | $H_{MPC}$ | Ref. $^a$ |
|-----------------|---------------|---------------|------------|-----------|----------|
| (26308) 1998 SM165 $^b$ | -             | 7.966         | 0.56       | 5.8       | R01      |
|                 | -             | 7.1           | 0.45       | ...       | S02      |
|                 | -             | 8.40±0.05     | 0.56       | ...       | S06      |
| (119979) 2002 WC19 $^b$ | -             | -             | <0.05      | 4.7       | S07      |
| (469505) 2003 FE128 $^c$ | -             | -             | <0.10      | ...       | T13      |
| (312645) 2010 EP65 $^c$ | 5.85±0.15    | -             | 0.50±0.14  | 6.4       | K06      |
|                 | 7.48          | 14.97         | 0.17±0.03  | 5.5       | B13      |

$^a$ References list:
R01: Romanishin et al. (2001), S02: Sheppard & Jewitt (2002), K06: Kern (2006), S06: Spencer et al. (2006), S07: Sheppard (2007), B13: Benecchi & Sheppard (2013), T13: Thirouin (2013).

$^b$ Known resolved wide binaries: Brown & Trujillo (2002), Noll et al. (2007), http://www2.lowell.edu/users/grundy/tnbs/469505_2003_FE128.html. 2010 EP65 was observed by HST program 12468 (PI: K.S. Noll) and no satellite was discovered.

$^c$ Several aliases are reported by Benecchi & Sheppard (2013).

$^5$ Orbital parameters computed by the Minor Planet Center for 1998 SM165 and 2006 SG369 are at https://minorplanetcenter.net/db_search/show_object?object_id=470083 and https://minorplanetcenter.net/db_search/show_object?object_id=26308

$^6$ The BVRI colors reported in Delsanti et al. (2001) were converted to $g'r'i'$ using the equations from Smith et al. (2002).
The mean rotational period of the binary systems is about 13.6 h. There is not enough full lightcurve of single objects to estimate the median period, but it seems that the binaries tend to rotate slower than the single objects in other dynamical populations (Thirouin & Sheppard 2019a, 2018; Thirouin et al. 2014).

4.4. Resolved and unresolved binaries

From this work, 2012 DX\textsubscript{98} is likely a nearly equal-sized contact binary whereas the lightcurve of 2002 VD\textsubscript{130} is best interpreted as a single triaxial object. But, the case of 1998 SM\textsubscript{165} has to be discussed in more detail. 1998 SM\textsubscript{165} has a large lightcurve amplitude of 0.56 mag (i.e., the same amplitude as 2012 DX\textsubscript{98}), but the lightcurve does not present the typical U- and V-shapes of a contact binary (Romanishin et al. 2001; Spencer et al. 2006). The lightcurve interpretation proposed by Romanishin et al. (2001) is that 1998 SM\textsubscript{165} is an irregularly-shaped object. Since the lightcurve publication, a small satellite has been discovered orbiting 1998 SM\textsubscript{165} (Grundy et al. 2011). To summarize, based on the large lightcurve amplitude of 1998 SM\textsubscript{165}, it can be a contact binary, but the lightcurve is not displaying the usual V- and U-shapes, and thus the lightcurve interpretation is still open to debate. Below, we will consider 1998 SM\textsubscript{165} as a contact binary and as an elongated object.

Sheppard & Jewitt (2004) estimated the fraction of contact binaries in the trans-Neptunian population using the following approach. The lightcurve amplitude of a small body with axis such as $a>b$ and $b=c$ varies with the angle of the object’s pole relative to the perpendicular of the line sight ($\theta$):

$$\Delta m = 2.5 \log \left( \frac{1 + \tan \theta}{(b/a) + \tan \theta} \right)$$

(1)

whereas the lightcurve amplitude of a triaxial ellipsoid varies as:

$$\Delta m = 2.5 \log \left( \frac{a}{b} \right) - 1.25 \log \left[ \left( \left( \frac{a}{b} \right)^2 - 1 \right) \sin^2 \theta + 1 \right]$$

(2)

Using Equation 1 and considering an object with $a/b=3$ (corresponding to a contact binary) has a lightcurve amplitude of 0.5 mag, we compute that $\theta$ has to be $\sim 36^\circ$. The probability that Earth would lie within $36^\circ$ of the equator of randomly oriented objects is $P(\theta \leq 36^\circ) \sim 0.59$. Using the same axis ratio and amplitude cut-off, Equation 2 infers $\theta \sim 34.5^\circ$, and $P(\theta \leq 34.5^\circ) \sim 0.57$. The amplitude cut-off of 0.5 mag was chosen based on the lightcurve amplitudes of 2012 DX\textsubscript{98} and 1998 SM\textsubscript{165}.

Excluding 2006 SG\textsubscript{415} from our sample (because its dynamical classification is uncertain), we have a total of 25 objects observed for lightcurve studies. Assuming that 2012 DX\textsubscript{98} is the only contact binary in the 2:1 resonance, the fraction of contact binaries is $f(\Delta m \geq 0.5 \text{mag}) \sim 1/(25 \times P(\theta)) \sim 7\%$ (same result with Equation 1 and 2). Including 1998 SM\textsubscript{165} as a contact binary, we estimate that $f(\Delta m \geq 0.5 \text{mag}) \sim 2/(25 \times P(\theta)) \sim 14\%$ using the previous equations. Therefore, we report a nearly equal-sized contact binary fraction at $\sim 7\%-14\%$ for the 2:1 resonance.
with Neptune. This is only a lower limit because of possible projection effects. Some nearly equal-sized contact binaries would still only show low amplitude lightcurves when observed near pole-on.

Noll et al. (2020) reported that the fraction of 2:1 resolved binaries with \( i < 12^\circ \) and an absolute magnitude between 5 and 8 mag is \( 27^{+10}_{-9} \% \) which is higher than the \( 5^{+6}_{-2} \% \) estimate for the 3:2 resonance, but similar to the fraction of resolved binaries in the dynamically Cold Classicals at \( 29^{+7}_{-6} \% \). Noll et al. (2020) also pointed out that the resolved binaries tend to be at higher inclinations in the 3:2 resonance. The use of the widely separated equal-sized systems in the trans-Neptunian belt to constrain Neptune’s migration was proposed by Murray-Clay & Schlichting (2011). If the migration-induced capture scenario is favored, some of the testable outcomes are (1) the 2:1 and 3:2 mean motion resonance with Neptune should have a low-inclination Cold Classical component, and (2) the low-inclination group in the 2:1 resonance should have a higher binary fraction than the high-inclination counterpart whereas the 3:2 low-inclination component should have a fraction \( \sim 20-30\% \) lower than the Cold Classicals. Sheppard (2012) demonstrated that both resonances have a Cold Classical component at low inclination based on color measurements, and the wide binary fractions reported by Noll et al. (2020) are also in agreement with a migration-induced capture scenario. Contact binaries are not considered by Murray-Clay & Schlichting (2011), but they are also at low to moderate inclinations (\(<20^\circ\)) in the 3:2 and the 2:1 resonances (Thirouin & Sheppard 2018). However, the higher fraction of contact binaries is in the 3:2, and not in the 2:1 as for the wide binaries.

Thirouin & Sheppard (2018) reported a nearly equal-sized contact binary fraction of \( ~40-50\% \) (corrected from projection effects) for the 3:2 mean motion resonance and Thirouin & Sheppard (2019a) inferred a fraction up to \( ~10-25\% \) (corrected from projection effects) for the dynamically Cold Classical. Therefore, the estimate for the 2:1 resonance is even lower than for the Cold Classical population, but as our 2:1 sample is smaller than the Cold Classical one, we will consider that the estimates for these two sub-populations are similarly low compared to the 3:2 resonance. Nesvorný & Vokrouhlický (2019) predicted a contact binary fraction between 10\% and 30\% for the excited TNO populations (as the 2:1 resonance), therefore our fraction is consistent with the lower range of the modeling estimate. Nesvorný & Vokrouhlický (2019) model only considers the collapse of a wide binary as the genesis of a contact binary which is not the only proposed mechanism to create these systems (Nesvorný & Vokrouhlický 2019; Porter & Grundy 2012; Nesvorný et al. 2010; Weidenschilling 2002; Goldreich et al. 2002). Also, the modeling is not focused on each TNO sub-populations, but rather on the Cold Classicals versus the excited populations. Therefore, there is a clear need for additional modeling efforts to understand the formation of contact binaries and their fractions across the trans-Neptunian belt.

The different contact binary fractions can also be due to the past history and interactions with Neptune of these three sub-populations (e.g., Morbidelli & Nesvorný (2020); Volk & Mahotra (2019); Nesvorný & Vokrouhlický (2019); Nesvorný (2015); Parker & Kavelaars (2010)). The Cold Classical population had very limited interactions with Neptune whereas the 3:2 was sculpted by these interactions. The 2:1 resonant objects were also likely affected by Neptune interactions in order to get them into resonance, but they present a low ratio of contact binaries, which is unlike the 3:2 resonance but similar to the Cold Classicals. This may suggest the 2:1’s Neptune interactions were not as strong as the 3:2 resonance’s Neptune interactions, as the 2:1 also has a large number of wide binaries, again similar to the less dynamically stirred Cold Classicals and unlike the 3:2 resonance population. More simulations on how the contact binaries form through Neptune’s interactions and/or migration is warranted.

### 4.5. Colors of large amplitude objects in the 2:1 resonance

Three objects, 1998 SM\(_{165}\), 2002 VD\(_{130}\), and 2012 DX\(_{98}\), have large lightcurve amplitudes from 0.31 to 0.56 mag.

Based on surface color measurements, 1998 SM\(_{165}\) is an ultra-red object (Delsanti et al. 2001; Peixinho et al. 2015). Thirouin & Sheppard (2019b) evaluated that the Sloan g’r’i’ surface colors of 2012 DX\(_{98}\) are g’-r’\(=0.85\pm0.06\) mag and g’-i’\(=1.25\pm0.06\) mag. Based on its very red colors which are typical of the dynamically Cold Classical population, Thirouin & Sheppard (2019b) suggested that 2012 DX\(_{98}\) is potentially an escaped Cold Classical.

On 2020 September 20UT, the g’r’i’ colors of 2002 VD\(_{130}\) were derived using the LDT. Its colors are g’-r’\(=1.03\pm0.06\) mag and g’-i’\(=1.35\pm0.06\) mag, which correspond to an ultra-red object. Therefore, all 3 objects with a large lightcurve amplitude have similar surface colors possibly linking them to the dynamically Cold Classicals (Thirouin & Sheppard 2019b).

### 5. SUMMARY AND CONCLUSIONS

The main results of this work are:
We report short-term variability of twenty-one 2:1 resonant TNOs. With our survey and the literature, we compile eighteen TNOs showing a low to high lightcurve amplitude.

We propose the first lightcurve of 2012 DX\textsubscript{98} which rotates in $\sim 21$ h and has a large amplitude of 0.56 mag. Based on its lightcurve morphology, 2012 DX\textsubscript{98} is likely a contact binary whose mass ratio is about 0.5.

The lightcurve of 2002 VD\textsubscript{130} with an amplitude of $\sim 0.3$ mag and periodicity of 9.85 h seems to be due to a single elongated object.

The contact binary fraction in the 2:1 resonance is very low, at $\sim 7$-14\% which is similar to the fraction in the Cold Classical population. Modeling from Nesvorný & Vokrouhlický (2019) suggested that excited TNO populations should have a fraction of contact binaries of 10-30\%. Therefore, estimates based on observations are consistent with the lower hand of the modeling results.

The surface g'v'i' colors of 2002 VD\textsubscript{130} and 2012 DX\textsubscript{98} are very red/ultra-red which is consistent with an origin in the dynamically Cold Classical population (Thirouin & Sheppard 2019b).

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**Facilities:** Lowell Discovery Telescope (LDT), Magellan-Baade Telescope

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APPENDIX

A. APPENDIX A
The photometry of all targets observed in this paper is available below. No light-time correction applied.

Table 3.

| TNO       | Julian Date   | Relative Magnitude [mag] | Error [mag] |
|-----------|---------------|--------------------------|-------------|
| 1999 RB   | 2459112.74797 | -0.07                    | 0.04        |
|           | 2459112.76947 | 0.01                     | 0.04        |
|           | 2459112.79098 | 0.05                     | 0.04        |
|           | 2459112.81929 | 0.08                     | 0.04        |
|           | 2459112.84876 | 0.01                     | 0.03        |
|           | 2459112.87824 | -0.07                    | 0.03        |
|           | 2459112.90750 | -0.05                    | 0.03        |
|           | 2459112.93563 | -0.07                    | 0.03        |
|           | 2459113.00314 | 0.00                     | 0.04        |
| 2000 QL   | 2458762.73490 | -0.04                    | 0.04        |
|           | 2458762.76565 | 0.03                     | 0.04        |
|           | 2458762.83763 | 0.03                     | 0.03        |
|           | 2458762.87612 | 0.00                     | 0.03        |
|           | 2458762.94669 | -0.04                    | 0.04        |
|           | 2458762.97795 | -0.12                    | 0.05        |
| 2001 FQ   | 2458254.51509 | 0.01                     | 0.05        |
|           | 2458254.53911 | -0.01                    | 0.05        |
|           | 2458254.58800 | -0.02                    | 0.05        |
|           | 2458254.61038 | -0.02                    | 0.05        |
|           | 2458254.63125 | -0.02                    | 0.05        |
|           | 2458254.68931 | 0.01                     | 0.06        |
|           | 2458254.74416 | 0.04                     | 0.06        |
|           | 2458254.78098 | 0.02                     | 0.06        |
|           | 2458254.81173 | 0.00                     | 0.06        |
| 2001 UP   | 2459116.76200 | 0.00                     | 0.10        |
|           | 2459116.78163 | 0.03                     | 0.11        |
|           | 2459116.81072 | 0.03                     | 0.10        |
|           | 2459116.83948 | 0.19                     | 0.10        |
|           | 2459116.86734 | 0.05                     | 0.10        |
|           | 2459116.89474 | -0.02                    | 0.09        |
|           | 2459116.92245 | -0.07                    | 0.10        |
|           | 2459116.95027 | -0.17                    | 0.10        |
|           | 2459116.97821 | -0.03                    | 0.10        |
|           | 2459139.71629 | -0.08                    | 0.07        |
|           | 2459139.81822 | -0.06                    | 0.07        |
|           | 2459139.86728 | 0.00                     | 0.07        |
|           | 2459139.89683 | 0.01                     | 0.08        |
|           | 2459139.94693 | 0.03                     | 0.08        |
|           | 2459139.97563 | 0.00                     | 0.08        |
|           | 2459140.00518 | 0.10                     | 0.10        |

Table 3 continued
Table 3 (continued)

| TNO  | Julian Date | Relative Magnitude [mag] | Error [mag] |
|------|-------------|--------------------------|-------------|
| 2002 PU_{170} |
| 2459112.65877 | -0.03 | 0.08 |
| 2459112.68620 | -0.03 | 0.07 |
| 2459112.71814 | 0.00 | 0.06 |
| 2459112.77651 | 0.02 | 0.06 |
| 2459112.83442 | 0.02 | 0.06 |
| 2459112.86365 | 0.01 | 0.07 |
| 2459112.89305 | 0.00 | 0.07 |

| 2002 VD_{130} |
| 2458836.89721 | -0.15 | 0.06 |
| 2458836.92818 | -0.10 | 0.06 |
| 2458836.94618 | -0.07 | 0.06 |
| 2458836.96362 | 0.00 | 0.06 |
| 2458836.98115 | 0.09 | 0.07 |
| 2458836.99845 | 0.10 | 0.06 |
| 2458837.01730 | 0.09 | 0.07 |
| 2458881.74653 | 0.14 | 0.06 |
| 2458881.76728 | 0.17 | 0.06 |
| 2458881.79936 | 0.11 | 0.06 |
| 2458881.83335 | -0.11 | 0.05 |
| 2458881.86067 | -0.24 | 0.04 |
| 2458881.88736 | -0.18 | 0.05 |
| 2459112.92134 | 0.10 | 0.05 |
| 2459112.94969 | -0.10 | 0.04 |
| 2459205.67903 | 0.01 | 0.04 |
| 2459205.70198 | -0.08 | 0.03 |
| 2459205.72354 | -0.19 | 0.03 |
| 2459205.74507 | -0.12 | 0.03 |
| 2459205.76718 | -0.10 | 0.03 |
| 2459205.78903 | -0.01 | 0.03 |
| 2459205.80974 | 0.10 | 0.03 |
| 2459205.83027 | 0.17 | 0.03 |
| 2459205.85085 | 0.11 | 0.03 |
| 2459205.87140 | 0.00 | 0.03 |
| 2459205.92695 | -0.19 | 0.03 |
| 2459205.94763 | -0.15 | 0.03 |
| 2459205.97008 | -0.06 | 0.03 |
| 2459205.98636 | 0.01 | 0.03 |
| 2459206.00259 | 0.00 | 0.03 |
| 2459206.01887 | 0.02 | 0.03 |
| 2459206.03494 | 0.14 | 0.04 |
| 2459206.04207 | 0.17 | 0.04 |
| 2459206.04917 | 0.17 | 0.05 |
| 2459232.61988 | -0.16 | 0.03 |
| 2459232.67510 | 0.02 | 0.03 |
| 2459232.72134 | 0.18 | 0.03 |
| 2459232.75327 | 0.04 | 0.03 |
| 2459232.80425 | -0.16 | 0.03 |
| 2459232.82945 | -0.11 | 0.03 |
| 2459232.85436 | -0.10 | 0.03 |
| 2459232.88012 | -0.01 | 0.03 |
| 2459232.90582 | 0.08 | 0.03 |

Table 3 continued
### Table 3 (continued)

| TNO   | Julian Date | Relative Magnitude [mag] | Error [mag] |
|-------|-------------|--------------------------|-------------|
| 2003 UP292 |
| 2458759.82999 | -0.05 | 0.03 |
| 2458759.85793 | -0.02 | 0.03 |
| 2458759.88218 | 0.01 | 0.03 |
| 2458759.90660 | 0.03 | 0.03 |
| 2458759.93094 | 0.00 | 0.03 |
| 2458759.95523 | 0.00 | 0.03 |
| 2458759.97936 | 0.00 | 0.03 |
| 2458760.00344 | 0.03 | 0.03 |
| 2458762.85756 | 0.02 | 0.02 |
| 2458762.89594 | -0.01 | 0.02 |
| 2458762.93457 | 0.04 | 0.03 |
| 2458762.96664 | 0.04 | 0.02 |
| 2458762.99734 | 0.00 | 0.02 |
| 2458893.59921 | 0.04 | 0.03 |
| 2458893.67778 | 0.00 | 0.02 |
| 2458893.71174 | -0.01 | 0.02 |
| 2458893.75144 | -0.02 | 0.02 |
| 2458893.78930 | 0.00 | 0.03 |

2006 SG369

| 2458759.82338 | -0.15 | 0.04 |
| 2458759.85116 | -0.22 | 0.04 |
| 2458759.87644 | -0.10 | 0.04 |
| 2458759.90056 | -0.12 | 0.04 |
| 2458759.92491 | 0.00 | 0.04 |
| 2458759.94936 | 0.02 | 0.04 |
| 2458759.97341 | 0.16 | 0.05 |
| 2458759.99745 | 0.10 | 0.04 |
| 2458760.01537 | 0.11 | 0.06 |
| 2458762.78258 | 0.02 | 0.04 |
| 2458762.81531 | 0.06 | 0.03 |

Table 3 continued
Table 3 (continued)

| TNO  | Julian Date | Relative Magnitude | Error |
|------|-------------|--------------------|-------|
|      |             | [mag]              | [mag] |
| 2458762.85389 | 0.04 | 0.03 |
| 2458762.89244 | 0.00 | 0.03 |
| 2458762.9102 | 0.00 | 0.03 |
| 2458762.96300 | -0.03 | 0.03 |
| 2458762.99376 | -0.03 | 0.03 |
| 2006 SG415 | | |
| 2458762.64956 | 0.08 | 0.06 |
| 2458762.66966 | 0.11 | 0.07 |
| 2458762.8007 | -0.11 | 0.03 |
| 2458762.86883 | 0.02 | 0.04 |
| 2458762.90713 | -0.08 | 0.04 |
| 2458762.63417 | 0.00 | 0.06 |
| 2011 EY90 | | |
| 2458989.70527 | 0.09 | 0.08 |
| 2458989.72632 | 0.00 | 0.06 |
| 2458989.75363 | 0.07 | 0.06 |
| 2458989.78008 | -0.01 | 0.06 |
| 2458989.80622 | 0.00 | 0.07 |
| 2012 DX98 | | |
| 2458254.50217 | -0.14 | 0.05 |
| 2458254.52781 | -0.14 | 0.04 |
| 2458254.55497 | -0.20 | 0.04 |
| 2458254.57684 | -0.19 | 0.04 |
| 2458254.59943 | -0.27 | 0.04 |
| 2458254.62117 | -0.24 | 0.04 |
| 2458254.67869 | -0.12 | 0.04 |
| 2458254.73377 | 0.05 | 0.05 |
| 2458255.48029 | -0.15 | 0.04 |
| 2458255.57953 | 0.01 | 0.04 |
| 2458255.62615 | 0.15 | 0.04 |
| 2458255.68974 | 0.26 | 0.04 |
| 2458255.77080 | 0.04 | 0.05 |
| 2458256.46938 | 0.01 | 0.04 |
| 2458256.49453 | 0.20 | 0.04 |
| 2458256.51369 | 0.20 | 0.05 |
| 2458256.55033 | 0.35 | 0.04 |
| 2458256.57975 | 0.27 | 0.04 |
| 2458256.60886 | 0.20 | 0.04 |
| 2458256.65415 | 0.03 | 0.04 |
| 2458256.69962 | -0.15 | 0.04 |
| 2458256.72320 | -0.17 | 0.04 |
| 2458256.74463 | -0.13 | 0.05 |
| 2458257.47652 | 0.24 | 0.05 |
| 2458257.48830 | 0.23 | 0.05 |
| 2458257.49420 | 0.15 | 0.05 |
| 2458257.51570 | 0.03 | 0.05 |
| 2458257.52153 | 0.04 | 0.04 |
| 2458257.54486 | -0.01 | 0.04 |
| 2458257.57767 | -0.15 | 0.04 |
| 2458257.58351 | -0.19 | 0.04 |
| 2458257.58940 | -0.19 | 0.04 |
| 2458257.61967 | -0.14 | 0.04 |

Table 3 continued
### Table 3 (continued)

| TNO       | Julian Date | Relative Magnitude [mag] | Error [mag] |
|-----------|-------------|--------------------------|-------------|
| 2012 KW₅₁ |             |                          |             |
| 2458988.67237 | 0.01          | 0.04                     |
| 2458988.69880 | 0.00          | 0.03                     |
| 2458988.73188 | -0.04         | 0.03                     |
| 2458988.75694 | -0.01         | 0.03                     |
| 2458988.79030 | 0.00          | 0.03                     |
| 2458988.82268 | -0.01         | 0.03                     |
| 2458988.85507 | 0.04          | 0.03                     |
| 2458988.88425 | 0.09          | 0.04                     |
| 2012 WE₃₇  |             |                          |             |
| 2459112.82663 | 0.00          | 0.06                     |
| 2459112.85552 | -0.02         | 0.06                     |
| 2459112.88510 | 0.01          | 0.06                     |
| 2459112.91424 | -0.04         | 0.05                     |
| 2459112.94239 | 0.03          | 0.05                     |
| 2012 XR₁₅₇ |             |                          |             |
| 2458817.78954 | 0.02          | 0.04                     |
| 2458817.81494 | -0.02         | 0.03                     |
| 2458817.84533 | 0.02          | 0.03                     |
| 2458817.85522 | -0.04         | 0.04                     |
| 2458818.59544 | 0.00          | 0.04                     |
| 2458818.63797 | 0.00          | 0.04                     |
| 2458818.67970 | -0.07         | 0.03                     |
| 2458893.68362 | 0.08          | 0.03                     |
| 2458893.71761 | 0.00          | 0.03                     |

**Table 3 continued**
| TNO | Julian Date | Relative Magnitude [mag] | Error [mag] |
|-----|-------------|--------------------------|-------------|
| 2013 GW136 | 245898.70526 | -0.06 | 0.04 |
| | 245898.73810 | -0.05 | 0.04 |
| | 245898.79652 | 0.00 | 0.04 |
| | 245898.82889 | 0.06 | 0.04 |
| | 245898.86515 | 0.11 | 0.05 |
| | 245899.83175 | -0.04 | 0.05 |
| | 245899.85723 | 0.04 | 0.05 |
| 2013 TG172 | 245911.27583 | -0.01 | 0.06 |
| | 245911.74100 | 0.05 | 0.06 |
| | 245911.78414 | 0.00 | 0.05 |
| | 245911.81243 | 0.06 | 0.05 |
| | 245911.84196 | 0.02 | 0.05 |
| | 245911.90053 | -0.03 | 0.05 |
| | 245911.92879 | 0.00 | 0.05 |
| | 245911.95725 | -0.01 | 0.06 |
| 2014 GB54 | 2458256.54462 | 0.04 | 0.05 |
| | 2458256.57386 | 0.01 | 0.05 |
| | 2458256.60303 | 0.01 | 0.04 |
| | 2458256.64606 | -0.01 | 0.05 |
| | 2458256.66951 | -0.04 | 0.05 |
| | 2458256.71785 | -0.05 | 0.06 |
| 2014 UT224 | 2458806.86524 | -0.03 | 0.03 |
| | 2458806.89122 | 0.00 | 0.04 |
| | 2458806.91727 | 0.05 | 0.05 |
| | 2458836.77668 | 0.00 | 0.03 |
| | 2458836.81671 | -0.03 | 0.03 |
| | 2458836.84798 | 0.01 | 0.03 |
| | 2458836.87970 | -0.11 | 0.04 |
| | 2458836.91051 | -0.06 | 0.06 |
| | 2458893.69049 | -0.05 | 0.04 |
| | 2458893.72372 | 0.00 | 0.04 |
| | 2458893.76271 | 0.04 | 0.05 |
| 2014 WT309 | 2458819.58651 | -0.21 | 0.04 |
| | 2458819.62462 | -0.16 | 0.04 |
| | 2458819.70264 | -0.04 | 0.04 |
| | 2458819.73390 | 0.04 | 0.04 |
| | 2458819.76861 | 0.04 | 0.04 |
| | 2458819.80816 | 0.06 | 0.04 |
| | 2458836.76352 | -0.06 | 0.05 |
| | 2458836.80983 | -0.06 | 0.05 |
| | 2458836.84161 | 0.13 | 0.08 |
| | 2458836.87335 | 0.00 | 0.08 |
| | 2458836.90418 | 0.12 | 0.12 |
| | 2459116.84736 | -0.06 | 0.06 |
| | 2459116.87499 | -0.07 | 0.06 |
| | 2459116.90246 | -0.01 | 0.06 |
| TNO         | Julian Date | Relative Magnitude [mag] | Error [mag] |
|------------|-------------|--------------------------|-------------|
| 2459116.93023 | 0.01        | 0.05                     |
| 2459116.95822 | 0.04        | 0.06                     |
| 2459116.98597 | 0.16        | 0.06                     |
| 2459139.85249 | -0.11       | 0.10                     |
| 2459139.88183 | -0.07       | 0.08                     |
| 2459139.91759 | 0.04        | 0.05                     |
| 2459139.96195 | 0.05        | 0.06                     |
| 2459139.99140 | 0.09        | 0.04                     |
| 2458893.72750 | 0.04        | 0.02                     |
| 2458893.76637 | 0.03        | 0.02                     |
| 2458893.79362 | 0.06        | 0.03                     |
| 2458893.82124 | 0.00        | 0.03                     |
| 2458893.84135 | -0.02       | 0.03                     |
| 2458893.86146 | -0.04       | 0.03                     |
| 2458893.90200 | 0.04        | 0.05                     |
| 2458893.69531 | -0.01       | 0.03                     |
APPENDIX B

Sparse lightcurves discussed in this paper are in Appendix B.
Figure 5. Objects in the 2:1 mean motion resonance with Neptune
Figure 6. Objects in the 2:1 mean motion resonance with Neptune
Figure 7. Objects in the 2:1 mean motion resonance with Neptune
Figure 8. Objects in the 2:1 mean motion resonance with Neptune
Figure 9. Objects in the 2:1 mean motion resonance with Neptune
Figure 10. Objects in the 2:1 mean motion resonance with Neptune