OSSOS. XII. Variability Studies of 65 Trans-Neptunian Objects Using the Hyper Suprime-Cam*

Mike Alexandersen¹ , Susan D. Benecchi² , Ying-Tung Chen (英同陳)¹ , Marielle R. Eduardo^{1,3} , Audrey Thirouin⁴ , Megan E. Schwamb⁵ , Matthew J. Lehner^{1,6,7} , Shiang-Yu Wang (王祥宇)¹ , Michele T. Bannister⁸ , Brett J. Gladman⁹, Stephen D. J. Gwyn¹⁰, JJ. Kavelaars^{10,11} , Jean-Marc Petit¹² , and Kathryn Volk¹³

¹ Institute of Astronomy and Astrophysics, Academia Sinica; 11F of AS/NTU Astronomy-Mathematics Building, No. 1 Roosevelt Rd., Sec. 4, Taipei 10617, Taiwan
mike.alexandersen@alumni.ubc.ca

² Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, USA

³ Department of Physical Sciences, University of the Philippines Baguio, Gov. Pack Rd., Baguio City, Benguet, 2600, Philippines

⁴ Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff, AZ 86001, USA

⁵ Gemini Observatory, Northern Operations Center, 670 North A'ohoku Pl., Hilo, HI 96720, USA

⁶ Department of Physics and Astronomy, University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, USA

⁷ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

⁸ Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK

⁹ Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada

¹⁰ Herzberg Astronomy and Astrophysics Research Centre, National Research Council of Canada, 5071 W. Saanich Rd., Victoria, British Columbia V9E 2E7, Canada

¹¹ Department of Physics and Astronomy, University of Victoria, Elliott Building, 3800 Finnerty Rd., Victoria, BC V8P 5C2, Canada

¹² Institut UTINAM UMR6213, CNRS, Univ. Bourgogne Franche-Comté, OSU Theta F-25000 Besançon, France

¹³ Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721, USA

Received 2018 July 2; revised 2018 December 11; accepted 2019 March 7; published 2019 September 19

Abstract

We present variability measurements and partial light curves of trans-Neptunian objects (TNOs) from a two-night pilot study using Hyper Suprime-Cam (HSC) on the Subaru Telescope (Maunakea, Hawaii, USA). Subaru's large aperture (8 m) and HSC's large field of view (1.77 deg²) allow us to obtain measurements of multiple objects with a range of magnitudes in each telescope pointing. We observed 65 objects with $m_r = 22.6$ –25.5 mag in just six pointings, allowing 20–24 visits of each pointing over the two nights. Our sample, all discovered in the recent Outer Solar System Origins Survey (OSSOS), spans absolute magnitudes of $H_r = 6.2$ –10.8 mag and thus investigates smaller objects than previous light curve projects have typically studied. Our data supports the existence of a correlation between the light curve amplitude and absolute magnitude seen in other works but does not support a correlation between the amplitude and orbital inclination. Our sample includes a number of objects from different dynamical populations within the trans-Neptunian region, but we do not find any relationship between variability and the dynamical class. We were only able to estimate periods for 12 objects in the sample and found that a longer baseline of observations is required for a reliable period analysis. We find that 31 objects (just under half of our sample) have variability of Δ_{mag} greater than 0.4 mag during all of the observations; in smaller 1.25 hr, 1.85 hr, and 2.45 hr windows, the median Δ_{mag} is 0.13, 0.16, and 0.19 mag, respectively. The fact that variability on this scale is common for small TNOs has important implications for discovery surveys (such as OSSOS or the Large Synoptic Survey Telescope) and color measurements.

Key words: Kuiper belt: general – minor planets, asteroids: general – planets and satellites: surfaces

Supporting material: extended figure, machine-readable tables

1. Introduction

Over the years, rotational light curves (the brightness variation versus time) from small bodies in our solar system have been used to derive physical properties about the shape, surface, cohesion, internal structure, and density of objects and to infer binarity (Sheppard et al. 2008; Thirouin et al. 2010; Benecchi & Sheppard 2013). Small light-curve amplitudes can be caused by albedo variation across the surface of a spherical object, but moderate/large amplitude light curves (maximum minus minimum, $\Delta_{\text{mag}} \geq 0.15$ –0.2 mag) are likely due to the shape of the object (Sheppard et al. 2008; Thirouin et al. 2010). Flat light curves can be explained by a nearly spherical object with a homogeneous surface or an elongated object with a pole-on orientation. A flat light curve can also be due to an extremely slow rotational period undetectable during the

observing window, and such a slow rotation may infer the presence of a companion (Thirouin et al. 2010, 2014; Benecchi & Sheppard 2013). Alternatively, very large amplitude light curves ($\Delta_{\text{mag}} \geq 0.9$ mag) with a U/V shape at the maximum/minimum of the brightness are due to close/contact binary systems (Sheppard & Jewitt 2004; Lacerda et al. 2014; Ryan et al. 2017; Thirouin et al. 2017; Thirouin & Sheppard 2017, 2018).

In the trans-Neptunian belt, four main dynamical populations—classical, resonant, detached, and scattering objects—have been identified with additional subdivisions inside some of these broad groupings. Resonant objects are trapped in mean-motion resonance with Neptune, such that the orbital period (or mean-motion) of the trans-Neptunian object (TNO) and Neptune have a small integer ratio, which causes the TNO to experience stabilizing gravitational perturbations. Objects that are currently interacting strongly with Neptune in such a way that their orbits are unstable are called scattering (a semimajor

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

Table 1
Field Centers Used in This Work

Field Identifier	R.A. (hr)	Decl. (deg)	Observations Night 1 Useful/Total	Observations Night 2 Useful/Total
LF07	00 ^h 31 ^m 33 ^s	+04°54′54″	12/12	10/12
LF08	00 ^h 41 ^m 41 ^s	+05°17′52″	12/12	10/12
LF09	00 ^h 42 ^m 34 ^s	+06°37′44″	12/12	10/12
LF10	00 ^h 45 ^m 37 ^s	+07°59′02″	12/12	10/12
LF11	01 ^h 10 ^m 00 ^s	+05°43′25″	10/10	9/10
LF12	01 ^h 21 ^m 51 ^s	+06°34′20″	10/10	9/10

Note. On the second night, each field lost one or two observations due to low transparency.

axis change of at least 1.5 au in 10 Myr is required for this classification in the nomenclature of Gladman et al. (2008). The detached objects are those objects with perihelia that are so distant that they are beyond significant gravitational influence from Neptune; how they got there is a subject of active research. The resonant, detached, and scattering objects are all dynamically excited (“hot”) populations, with wide inclination and eccentricity distributions, and are thought to have been caused by significant interaction with the giant planets or other small bodies during the era of planetary migration (Kaula & Newman 1992; Malhotra 1993, 1995; Thommes et al. 2002; Kortenkamp et al. 2004; Hahn & Malhotra 2005; Murray-Clay & Chiang 2005; Tsiganis et al. 2005; Levison et al. 2008). The classical objects consists of nonresonant, non-scattering objects, primarily located at semimajor axes between 42 and 48 au. The classical population has both a hot subpopulation and a dynamically cold subpopulation of objects that have nearly circular orbits with low inclinations and eccentricities; the dynamically cold objects likely had only limited interactions with the giant planets. Due to their different formation mechanisms, it is possible that these dynamical populations have different light-curve properties, just as they have different color distributions (Trujillo & Brown 2002; Peixinho et al. 2003; Fraser & Brown 2012; Sheppard 2012; Tegler et al. 2016; Pike et al. 2017).

Because light curves of TNOs have been studied by several surveys over the past decades, it is now possible to study the rotational properties of the different dynamical populations. Several studies have identified different correlations/anticorrelations between orbital and physical/rotational properties, allowing us to understand the different dynamical environments in the trans-Neptunian belt (Duffard et al. 2009; Benecchi & Sheppard 2013; Thirouin et al. 2016). However, most of the past surveys focused on bright objects, as they are the easiest ones to study with small/moderate aperture facilities. Therefore, we present a pilot study using the Subaru/Hyper Suprime-Cam (HSC) to study the rotational properties of the faint TNOs ($H_r > 8.0$ mag). We aim to explore the rotational properties of TNOs in several size ranges, particularly for smaller objects around the break in each population’s size distribution (Shankman et al. 2013; Fraser et al. 2014; Alexandersen et al. 2016; Lawler et al. 2018); however, firm conclusions will require additional observations.

2. Sample and Observations

Our sample consists entirely of objects discovered or detected in the Outer Solar System Origins Survey (OSSOS; Bannister et al. 2016, 2018). OSSOS was a large program on

the Canada–France–Hawaii Telescope (CFHT), which ran from 2013 through 2017. OSSOS detected and tracked more than 800 trans-Neptunian objects with regular follow-up observations during at least two years to determine accurate orbits and secure dynamical classifications (Bannister et al. 2018). Due to the design and success of OSSOS, we have very complete information on the orbital characteristics and classification of these objects. Likewise, because these objects were discovered recently, they are still tightly clustered on the sky, having only slightly diffused apart due to *Kepler* shear. This allows us to observe up to 17 objects at once within the 1.77 deg² field of view of Subaru Telescope’s HSC (Miyazaki et al. 2018). The six fields used in this study (coordinates in Table 1) were chosen in order to maximize the number of objects within each field (see Figure 1), for a total of 63 TNOs (37 classical, 15 resonant, 5 detached, and 6 scattering) and two Centaurs spanning apparent magnitudes of $m_r = 22.6$ –25.5 mag and absolute magnitudes of $H_r = 6.2$ –10.8 mag (as calculated from our light-curve observations). This sample far outnumbers (by a factor of 2.5) previously reported variability studies for faint ($H_r \geq 8$ mag) TNOs. Our sample thus much more thoroughly probes a smaller size regime than previous light-curve studies have typically studied, thanks to the combined aperture size and field of view of Subaru/HSC. Information about the individual objects in our sample can be found in Table 2.

Data were collected by M. Alexandersen and S.-Y. Wang on the nights of 2016 August 25 and 26, using HSC on Subaru Telescope, located on Maunakea, Hawaii, USA.¹⁴ Figure 1 shows our field locations in relation to the swarm of OSSOS TNOs. As TNOs are typically brightest in the r band, this filter was used. The six fields were observed in a repeated sequence with one 300 s exposure of each field, resulting in about 36 minutes between repeat observations of the same field. Because the observing nights were approximately 1.5 months from opposition, we were unable to observe our fields for the entire night; the four fields closer to opposition thus were observed 12 times each night, while two other fields were observed 10 times each night. Observations were taken at air masses ranging from 1.02 to 2.04. The conditions were generally good (transparency near 1.0, with the seeing mostly between 0″.65 and 1″.0), apart from about one hour of clouds and very low transparency on the second night. One or two observations of each field were, therefore, unusable for this project.

¹⁴ All data obtained as part of this project can be downloaded from <https://smoka.nao.ac.jp/fssearch> or <http://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/search/>.

Figure 1. Location of our 2016 fields relative to TNOs discovered in the OSSOS L and S blocks (left and right, respectively). The large field of view of HST (magenta) allowed us to observe many objects at once. The field centers used are listed in Table 1.

3. Photometry and Calibration

Images were processed using `hscPipe`,¹⁵ the official HSC data reduction software package, which includes calibration of astrometry/photometry and basic image processing (bias, darks, and flats; Bosch et al. 2018). `hscPipe` was developed as a prototype pipeline for the Large Synoptic Survey Telescope (LSST) project (Ivezic et al. 2019). The algorithms and conceptions of `hscPipe` were inherited from the Sloan Digital Sky Survey (SDSS) Photo Pipeline (Lupton et al. 2001). The standard outputs of the `hscPipe` process include detection catalogs and calibrated images. We used the Pan-STARRS1 PV2 catalog (PS1; Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013) as the reference catalog for photometry and astrometry.

Photometry of bright point sources revealed systematic variability (of the order of 0.01 mag), caused by the fact that `hscPipe` calibrates images individually; images of the same field can thus have slight discrepancies relative to each other due to uncertainties in the zero-point determinations. To mitigate for this effect, background stars were inspected to find a set of 10–15 nonvariable stars, defined as those that exhibit similar systematic variability, to reveal the systematic variability of the zero-point error. A secondary correction was then applied to the zero-points, such that the average magnitude of the nonvariable stars is constant across the set of images. This adjustment was typically smaller than 0.02 mag but is important for obtaining the most accurate TNO photometry possible.

In order to get the best possible photometric measurements of our TNOs, we used the Python package `TRIPTY` (Fraser et al. 2016). TNOs move at typical rates of 3″–6″/hr at opposition, thus moving up to 0″.5 during our 300 s exposures, causing slight trailing. `TRIPTY` uses knowledge of the rate and angle of motion to accurately measure photometry for moving objects using an elongated aperture and appropriate aperture correction.

We obtained 9–23 useful measurements for each object over two nights; the median number of measurements per object is 19. One or two images per field were discarded due to low transparency during one hour on the second night; while some reduced transparency can be corrected for in calibration, we found that images with transparency <50% consistently produced anomalous results, so we chose to exclude those images. Many objects lost one

or more measurement due to being too close to a background source for reliable photometry. Three objects (2015 RE₂₈₀, 2000 QH₂₂₆, and 2015 RR₂₇₈) only have data on one night because they fell into chip gaps on one of the two nights; this was difficult to avoid when optimizing field location for up to 17 objects moving at different rates. One object (2015 RZ₂₇₉) was on a different chip on the two nights; however, we are confident that our zero-point calibration is accurate such that there is not an offset between the two nights. The final calibrated photometric measurements as well as the calibrated zero-points can be found in Table 3.

4. Results

We measured partial light curves for 63 TNOs and two Centaurs. The measurements can be found in graphical form in Figures 2–6; the photometric data can be found in Table 3. Several objects (such as 2013 UL₁₅, 2015 RO₂₈₁, 2003 SP₃₁₇, 2015 RB₂₈₀, and 2013 UN₁₅) feature clear, high-amplitude variability. We investigated the relationships between our measured light-curve variability and other properties, such as the absolute magnitude, dynamical class, and other orbital parameters (Section 4.1). For the best quality light curves, estimates of the rotation periods were also made (Section 4.2).

In order to estimate the uncertainty on parameters, such as the magnitude variation, period, correlation coefficient, and so on, a resampling method was used. One thousand resampled data sets were generated by resampling each magnitude measurement of each object. This resampling was drawn from a normal distribution centered on the measured value with a width equal to the measurement uncertainty. The analysis was then performed on each resampled data set independently to find the distribution of resultant values. The 2σ uncertainty on a value is then taken to be the range that spans the central 95% of values (i.e., 2.5% in each tail).

4.1. Amplitude Analysis

The mean rotational period of TNOs has been found to be 7–9 hr (Duffard et al. 2009; Benecchi & Sheppard 2013; Thirouin et al. 2016), although periods range from 3.9 hr (Haumea) to 154 hr (Pluto). While we do not have full light curves for all of our target objects, the mean period of 7–9 hr means that we likely observed a near-maximum and near-minimum of most of our target objects. Simple simulations of

¹⁵ https://hscdata.mtk.nao.ac.jp:4443/hsc_bin_dist/index.html

Table 2
Summary of Information about the Objects in our Sample

ID	Field	a (au)	e	i (deg)	Class	MPC	m_r (mag)	H_r (mag)	Δ_{mag}	σ_{mag}
o5t09PD	LF09	67.760 $\pm$ 0.009	0.459	3.575	det	2014 UA ₂₂₅	22.627 $\pm$ 0.002	7.033	0.110 ^{+0.012} _{-0.012}	0.027 ^{+0.002} _{-0.002}
o3l43	LF11	45.785 $\pm$ 0.004	0.097	2.025	cla	2013 UL ₁₅	22.989 $\pm$ 0.002	6.702	0.363 ^{+0.012} _{-0.011}	0.109 ^{+0.002} _{-0.002}
o5s21	LF10	43.851 $\pm$ 0.007	0.170	2.373	cla	2015 RO ₂₈₁	23.225 $\pm$ 0.003	7.564	0.36 ^{+0.02} _{-0.02}	0.106 ^{+0.003} _{-0.003}
o3l57	LF12	45.044 $\pm$ 0.004	0.075	1.841	res 11:6	2013 UM ₁₅	23.297 $\pm$ 0.003	6.872	0.127 ^{+0.015} _{-0.014}	0.034 ^{+0.003} _{-0.003}
o5t03	LF09	25.967 $\pm$ 0.0014	0.288	18.849	cen	2015 RD ₂₇₇	23.380 $\pm$ 0.003	10.825	0.15 ^{+0.03} _{-0.02}	0.041 ^{+0.004} _{-0.004}
o5t34PD	LF07	45.959 $\pm$ 0.003	0.170	5.081	res 17:9	2003 SP ₃₁₇	23.511 $\pm$ 0.006	7.226	0.56 ^{+0.05} _{-0.04}	0.177 ^{+0.007} _{-0.006}
o5s07	LF08	39.332 $\pm$ 0.004	0.249	16.270	res 3:2	2015 RU ₂₇₇	23.615 $\pm$ 0.004	8.957	0.22 ^{+0.02} _{-0.02}	0.048 ^{+0.004} _{-0.003}
o5s52	LF10	50.85 $\pm$ 0.03	0.247	27.196	res 11:5	2015 RU ₂₇₈	23.616 $\pm$ 0.003	7.054	0.314 ^{+0.014} _{-0.014}	0.094 ^{+0.003} _{-0.003}
o5s36	LF09	43.258 $\pm$ 0.003	0.053	2.206	cla	2015 RB ₂₈₁	23.638 $\pm$ 0.003	7.569	0.43 ^{+0.02} _{-0.02}	0.128 ^{+0.004} _{-0.004}
o5s05	LF10	21.981 $\pm$ 0.010	0.479	15.389	cen	2015 RV ₂₄₅	23.640 $\pm$ 0.004	10.767	0.10 ^{+0.02} _{-0.02}	0.025 ^{+0.004} _{-0.004}
o3l64	LF11	44.355 $\pm$ 0.003	0.073	1.972	cla	2013 UW ₁₆	23.729 $\pm$ 0.004	7.233	0.13 ^{+0.02} _{-0.02}	0.038 ^{+0.004} _{-0.004}
o3l46	LF12	46.612 $\pm$ 0.004	0.079	2.471	cla	2013 UP ₁₅	23.730 $\pm$ 0.004	7.404	0.29 ^{+0.02} _{-0.02}	0.089 ^{+0.004} _{-0.004}
o5t08	LF08	38.848 $\pm$ 0.003	0.057	1.097	cla	2015 RY ₂₇₈	23.751 $\pm$ 0.004	8.164	0.21 ^{+0.02} _{-0.02}	0.057 ^{+0.004} _{-0.004}
o5t30	LF08	43.791 $\pm$ 0.008	0.073	2.170	cla	2015 RB ₂₈₀	23.811 $\pm$ 0.004	7.648	0.55 ^{+0.02} _{-0.02}	0.159 ^{+0.005} _{-0.005}
o5t42	LF07	39.451 $\pm$ 0.011	0.204	1.587	res 3:2	2000 QA ₂₄₃	23.833 $\pm$ 0.004	7.254	0.16 ^{+0.02} _{-0.02}	0.045 ^{+0.004} _{-0.004}
o5s14	LF07	34.841 $\pm$ 0.002	0.047	7.122	res 5:4	2015 RN ₂₇₈	23.911 $\pm$ 0.004	8.488	0.22 ^{+0.02} _{-0.02}	0.054 ^{+0.004} _{-0.004}
o5t51	LF08	59.83 $\pm$ 0.10	0.425	13.851	res 14:5	2015 RG ₂₇₉	23.936 $\pm$ 0.004	6.833	0.24 ^{+0.03} _{-0.02}	0.057 ^{+0.004} _{-0.004}
o3l82	LF11	43.657 $\pm$ 0.005	0.286	24.987	res 7:4	2013 UK ₁₇	23.936 $\pm$ 0.005	6.621	0.15 ^{+0.02} _{-0.02}	0.044 ^{+0.006} _{-0.005}
o3l63	LF12	45.132 $\pm$ 0.004	0.054	3.363	cla	2013 UN ₁₅	23.986 $\pm$ 0.005	7.493	0.56 ^{+0.03} _{-0.03}	0.161 ^{+0.005} _{-0.004}
o3l83	LF11	200.2 $\pm$ 0.5	0.781	10.652	det	2013 UT ₁₅	24.001 $\pm$ 0.005	6.168	0.33 ^{+0.02} _{-0.02}	0.098 ^{+0.005} _{-0.005}
o5s35	LF09	46.40 $\pm$ 0.02	0.161	24.307	cla	2015 RC ₂₇₇	24.065 $\pm$ 0.005	8.023	0.37 ^{+0.03} _{-0.03}	0.106 ^{+0.005} _{-0.005}
o3l55	LF11	44.004 $\pm$ 0.004	0.096	2.358	cla	2013 UY ₁₆	24.086 $\pm$ 0.005	7.667	0.37 ^{+0.02} _{-0.02}	0.121 ^{+0.005} _{-0.005}
o5t16	LF08	44.79 $\pm$ 0.02	0.176	17.756	cla	2015 RY ₂₇₉	24.158 $\pm$ 0.005	8.358	0.36 ^{+0.04} _{-0.03}	0.093 ^{+0.006} _{-0.006}
o5s30	LF07	41.477 $\pm$ 0.005	0.073	33.327	cla	2015 RR ₂₈₀	24.164 $\pm$ 0.007	8.247	0.27 ^{+0.03} _{-0.03}	0.063 ^{+0.006} _{-0.006}
o3l71	LF12	45.319 $\pm$ 0.003	0.014	1.927	cla	2013 UW ₁₇	24.178 $\pm$ 0.006	7.612	0.42 ^{+0.03} _{-0.03}	0.125 ^{+0.006} _{-0.005}
o5t06	LF08	72.06 $\pm$ 0.03	0.535	12.327	sca	2015 RZ ₂₇₈	24.183 $\pm$ 0.006	8.941	0.25 ^{+0.03} _{-0.03}	0.069 ^{+0.006} _{-0.006}
o5s22	LF10	46.162 $\pm$ 0.010	0.222	8.482	res 19:10	2015 RG ₂₈₁	24.207 $\pm$ 0.005	8.538	0.21 ^{+0.02} _{-0.02}	0.059 ^{+0.005} _{-0.005}
o5s15	LF07	45.439 $\pm$ 0.009	0.238	25.362	res 13:7	2015 RO ₂₇₈	24.246 $\pm$ 0.006	8.809	0.31 ^{+0.03} _{-0.03}	0.084 ^{+0.006} _{-0.006}
o3l65	LF11	44.609 $\pm$ 0.007	0.278	11.207	sca	2013 UZ ₁₆	24.272 $\pm$ 0.006	7.775	0.36 ^{+0.03} _{-0.03}	0.095 ^{+0.007} _{-0.007}
o3l20	LF12	39.425 $\pm$ 0.010	0.181	2.085	res 3:2	2013 UV ₁₇	24.335 $\pm$ 0.008	8.354	0.69 ^{+0.04} _{-0.04}	0.185 ^{+0.008} _{-0.008}
o5s19	LF10	45.054 $\pm$ 0.006	0.194	17.960	res 11:6	2015 RT ₂₇₈	24.357 $\pm$ 0.006	8.758	0.38 ^{+0.03} _{-0.03}	0.105 ^{+0.006} _{-0.006}
o5t10	LF07	37.844 $\pm$ 0.006	0.051	1.540	cla	2015 RW ₂₇₈	24.375 $\pm$ 0.007	8.768	0.31 ^{+0.05} _{-0.04}	0.081 ^{+0.008} _{-0.008}
o5t44	LF08	43.560 $\pm$ 0.004	0.071	3.566	cla	2015 RZ ₂₇₉	24.383 $\pm$ 0.007	7.768	0.28 ^{+0.03} _{-0.03}	0.085 ^{+0.005} _{-0.005}
o3l62	LF11	39.230 $\pm$ 0.004	0.238	4.416	res 3:2	2013 UX ₁₆	24.415 $\pm$ 0.008	7.950	0.27 ^{+0.05} _{-0.04}	0.076 ^{+0.010} _{-0.010}
o5s24	LF10	50.376 $\pm$ 0.018	0.278	9.376	res 13:6	2015 RV ₂₇₈	24.435 $\pm$ 0.007	8.657	0.58 ^{+0.04} _{-0.04}	0.153 ^{+0.007} _{-0.007}
o3l19	LF11	45.334 $\pm$ 0.003	0.126	1.480	cla	2013 SM ₁₀₀	24.447 $\pm$ 0.007	8.507	0.68 ^{+0.04} _{-0.04}	0.174 ^{+0.007} _{-0.007}
o5s42	LF10	39.323 $\pm$ 0.011	0.165	5.772	res 3:2	2015 RV ₂₇₇	24.482 $\pm$ 0.007	8.284	0.38 ^{+0.05} _{-0.04}	0.102 ^{+0.009} _{-0.010}
o5t27	LF08	43.907 $\pm$ 0.011	0.079	1.498	cla	2015 RW ₂₇₉	24.490 $\pm$ 0.007	8.348	0.42 ^{+0.04} _{-0.04}	0.101 ^{+0.006} _{-0.006}
o5t48	LF07	42.183 $\pm$ 0.003	0.156	5.209	res 5:3	2015 RJ ₂₇₈	24.526 $\pm$ 0.011	7.693	0.41 ^{+0.04} _{-0.04}	0.107 ^{+0.009} _{-0.009}
o5t13	LF08	79.06 $\pm$ 0.03	0.535	17.629	res 17:4	2015 RL ₂₇₈	24.531 $\pm$ 0.007	8.849	0.41 ^{+0.05} _{-0.05}	0.100 ^{+0.008} _{-0.008}
o5t32	LF08	43.791 $\pm$ 0.005	0.035	2.209	cla	2015 RT ₂₇₉	24.537 $\pm$ 0.008	8.292	0.48 ^{+0.05} _{-0.05}	0.117 ^{+0.010} _{-0.010}
o3l84	LF11	44.012 $\pm$ 0.003	0.082	1.435	cla	2013 UR ₂₂	24.547 $\pm$ 0.009	7.858	0.44 ^{+0.06} _{-0.06}	0.117 ^{+0.011} _{-0.010}
o3l44	LF12	42.793 $\pm$ 0.005	0.042	2.940	cla	2013 UC ₁₈	24.557 $\pm$ 0.008	8.261	0.47 ^{+0.04} _{-0.04}	0.141 ^{+0.010} _{-0.009}
uo3l88	LF11	43.935 $\pm$ 0.004	0.081	2.479	cla	2013 ST ₁₀₂	24.558 $\pm$ 0.007	8.275	0.53 ^{+0.04} _{-0.05}	0.169 ^{+0.009} _{-0.008}
o5t07	LF07	39.513 $\pm$ 0.009	0.192	2.802	res 3:2	2000 QH ₂₂₆	24.611 $\pm$ 0.014	9.159	0.48 ^{+0.06} _{-0.06}	0.143 ^{+0.015} _{-0.014}
o5t41	LF08	44.310 $\pm$ 0.004	0.043	0.997	cla	2015 RE ₂₈₀	24.659 $\pm$ 0.011	8.085	0.23 ^{+0.05} _{-0.04}	0.068 ^{+0.012} _{-0.009}
o5t22	LF08	39.58 $\pm$ 0.02	0.176	5.457	res 3:2	2015 RT ₂₇₇	24.664 $\pm$ 0.009	8.612	0.28 ^{+0.05} _{-0.03}	0.076 ^{+0.009} _{-0.008}
o5t49	LF08	44.851 $\pm$ 0.004	0.096	1.968	cla	2015 RA ₂₈₀	24.672 $\pm$ 0.008	7.807	0.64 ^{+0.04} _{-0.04}	0.204 ^{+0.008} _{-0.008}
o5s61	LF10	44.942 $\pm$ 0.012	0.117	3.023	cla	2015 RP ₂₈₁	24.696 $\pm$ 0.009	7.879	0.65 ^{+0.05} _{-0.04}	0.177 ^{+0.009} _{-0.009}
o5t23	LF08	46.215 $\pm$ 0.007	0.132	5.089	cla	2015 RU ₂₇₉	24.813 $\pm$ 0.009	8.760	0.66 ^{+0.08} _{-0.06}	0.174 ^{+0.012} _{-0.012}
o5s40	LF09	44.310 $\pm$ 0.007	0.075	2.276	cla	2015 RK ₂₈₁	24.965 $\pm$ 0.010	8.702	0.41 ^{+0.05} _{-0.04}	0.117 ^{+0.009} _{-0.009}
o5t26	LF09	43.173 $\pm$ 0.004	0.043	16.024	cla	2015 RX ₂₇₉	24.973 $\pm$ 0.013	8.855	0.41 ^{+0.07} _{-0.05}	0.115 ^{+0.014} _{-0.014}
uo5t55	LF08	44.25 $\pm$ 0.02	0.073	1.544	cla	2015 RR ₂₈₁	25.015 $\pm$ 0.011	8.702	0.54 ^{+0.08} _{-0.07}	0.129 ^{+0.013} _{-0.013}
o5s29	LF07	41.396 $\pm$ 0.003	0.045	34.929	cla	2015 RO ₂₈₀	25.023 $\pm$ 0.012	9.111	0.33 ^{+0.05} _{-0.04}	0.097 ^{+0.011} _{-0.011}
o5s43	LF07	70.84 $\pm$ 0.07	0.465	10.192	det	2015 RH ₂₇₉	25.044 $\pm$ 0.011	8.837	0.49 ^{+0.07} _{-0.08}	0.120 ^{+0.014} _{-0.015}
o5t25	LF08	43.288 $\pm$ 0.006	0.047	0.461	cla	2015 RC ₂₈₀	25.084 $\pm$ 0.012	8.971	0.40 ^{+0.06} _{-0.06}	0.099 ^{+0.011} _{-0.011}
o5t21	LF08	43.633 $\pm$ 0.003	0.074	6.872	res 7:4	2015 RE ₂₇₈	25.104 $\pm$ 0.014	9.082	0.59 ^{+0.07} _{-0.06}	0.165 ^{+0.013} _{-0.013}
o5s55	LF09	46.93 $\pm$ 0.02	0.173	4.812	cla	2015 RH ₂₈₁	25.107 $\pm$ 0.010	8.528	0.59 ^{+0.07} _{-0.06}	0.148 ^{+0.011} _{-0.010}

Table 2
(Continued)

ID	Field	a (au)	e	i (deg)	Class	MPC	m_r (mag)	H_r (mag)	Δ_{mag}	σ_{mag}
o5s26	LF09	41.344 ± 0.007	0.112	17.483	cla	2015 RD ₂₈₁	25.111 ± 0.014	9.299	$0.54^{+0.05}_{-0.05}$	$0.152^{+0.012}_{-0.012}$
o5s12	LF10	34.791 ± 0.005	0.100	2.668	res 5:4	2015 RR ₂₇₈	25.118 ± 0.015	9.798	$0.40^{+0.08}_{-0.06}$	$0.13^{+0.02}_{-0.02}$
o5s49	LF07	44.017 ± 0.007	0.044	2.088	cla	2015 RQ ₂₈₀	25.178 ± 0.012	8.889	$1.01^{+0.10}_{-0.09}$	$0.22^{+0.02}_{-0.02}$
o5s60	LF10	42.530 ± 0.007	0.128	40.362	cla	2015 RN ₂₈₁	25.180 ± 0.012	8.510	$0.51^{+0.07}_{-0.06}$	$0.127^{+0.012}_{-0.012}$
o5t24	LF09	44.953 ± 0.006	0.107	2.398	cla	2015 RH ₂₈₀	25.257 ± 0.014	9.199	$0.80^{+0.08}_{-0.08}$	$0.20^{+0.02}_{-0.02}$
o5s57	LF07	41.356 ± 0.011	0.140	32.358	cla	2015 RW ₂₈₀	25.276 ± 0.016	8.649	$0.84^{+0.10}_{-0.09}$	$0.227^{+0.016}_{-0.015}$
uo5s77	LF09	65.95 ± 0.11	0.413	38.607	res 13:4	2015 RS ₂₈₁	25.604 ± 0.018	9.477	$0.98^{+0.09}_{-0.09}$	$0.295^{+0.02}_{-0.02}$

Note. *ID* refers to the internal OSSOS designation (as used in (Bannister et al. 2018)). *Field* is the field in which the target was observed (Table 1). a , e and i are the barycentric orbital parameters semi-major axis, eccentricity and inclination (uncertainties on eccentricity and inclination are always 0.001 or smaller and are therefore not listed here). *Class* is the dynamical classification of the object. *MPC* is the Minor Planet Center (<https://minorplanetcenter.net/iau/mpc.html>) designation (Note: all objects will have MPC designations before the publication of this work). m_r and H_r are the mean apparent and absolute magnitudes of the objects, as measured in this work (these are the magnitudes used everywhere in this paper, as they are more accurate than the discovery magnitudes from OSSOS); due to the quality of the OSSOS orbits, the uncertainty on H_r is identical to that of m_r to the given precision. Δ_{mag} is the maximum magnitude variation measured for the object within this work. σ_{mag} is the standard deviation of the magnitudes measured in this work. This table is ordered in the same order as Figures 3 to 6: brightest object at the top to faintest object at the bottom.

(This table is available in machine-readable form.)

Table 3
Photometric Measurements from This HSC Data Set

MJD-57620	$m_r \pm \sigma_{\text{Rand}}$	$Zp \pm \sigma_{\text{Sys}}$
o3l19, 2013 SM ₁₀₀		
6.3913125	24.09 ± 0.03	26.995 ± 0.005
6.4154337	24.21 ± 0.02	27.012 ± 0.005
6.4393438	24.45 ± 0.02	27.022 ± 0.005
6.4634385	24.69 ± 0.04	27.058 ± 0.005
6.4876346	24.78 ± 0.03	27.047 ± 0.005
6.5123402	24.56 ± 0.03	27.039 ± 0.005
6.5375195	24.41 ± 0.03	27.043 ± 0.005
6.5628085	24.29 ± 0.03	27.045 ± 0.005
6.5875091	24.28 ± 0.02	27.038 ± 0.005
7.3876072	24.55 ± 0.03	26.978 ± 0.005
7.4114040	24.67 ± 0.03	27.002 ± 0.005
7.4353624	24.45 ± 0.02	26.885 ± 0.005
7.4595078	24.47 ± 0.02	26.869 ± 0.005
7.5081300	24.36 ± 0.03	26.497 ± 0.005
7.5584662	24.35 ± 0.02	27.019 ± 0.005
7.5830743	24.42 ± 0.02	27.004 ± 0.005
7.6079518	24.58 ± 0.02	26.994 ± 0.005

Note. σ_{Rand} is the random uncertainty of the m_r magnitude measurement. Zp is the zero-point used. σ_{Sys} is the systematic uncertainty on the zero-point (and thus also on the measurement). This is an example for a single object; all measurements from all 65 objects are available in machine readable format.

(This table is available in its entirety in machine-readable form.)

our observations confirm that for objects of a given period between 3 and 40 hr, we observe more than 80% of the variability on average (averaged over the random starting phase); for periods between 3 and 22 hr, we observe more than 88% of the variability on average. It is thus reasonable to assume that our measurements of Δ_{mag} (the maximum minus the minimum magnitude) are close to the full light-curve amplitudes and that the slight underestimation will not affect our results (such as whether or not correlations exist). In this subsection, we removed the two Centaurs (2015 RV₂₄₅ and 2015 RD₂₇₇) from the sample, because the surface and rotation of these objects might have been altered by close approaches to

the Sun or planets (Duffard et al. 2009; Thirouin et al. 2010). As an alternative to the difference between the brightest and faintest observation (Δ_{mag}), we also examine the standard deviation (σ_{mag}) of all the observations of each object, because the standard deviation is a measure of overall variation that is less influenced by individual anomalous measurements.

In Figure 7, we plot both Δ_{mag} and σ_{mag} versus object H_r , semimajor axis a , and inclination i to illustrate possible relations between these parameters. In a sample of 128 objects, Benecchi & Sheppard (2013) found a statistically significant correlation ($\rho = 0.288$ and $P = 0.001$) between the light-curve amplitude and absolute magnitude. Their sample spanned absolute magnitudes from 0 to 12 mag, although most were between 4 and 7 mag; very few had absolute magnitudes fainter than 8 mag. Our sample of 63 TNOs span $H_r = 6.2$ –10.8 mag,¹⁶ with more than half the sample at $H_r > 8.0$ mag; our sample thus represents variability properties for fainter TNOs than the bulk of the Benecchi & Sheppard (2013) sample. Using the Spearman Rank correlation test (Spearman 1904) and our independent sample of 63 TNOs, we find $\rho = 0.37$ and $P = 0.003$ for Δ_{mag} versus H_r and $\rho = 0.31$ and $P = 0.013$ for σ_{mag} versus H_r . Our data thus strongly support the existence of a weak relationship where intrinsically fainter (likely smaller) bodies, on average, have larger light-curve amplitudes. This is likely due to increasingly elongated shapes. Benecchi & Sheppard (2013) also found a borderline significant anticorrelation ($\rho = -0.170$ and $P = 0.056$) between the light-curve amplitude and inclination (i); however, our data do not support the existence of such an anticorrelation.

Because the cold classicals are thought to have formed in place while all the hot populations (hot classicals, resonant, detached, and scattering) are thought to have been scattered outward to some extent after having formed closer to the Sun (e.g., Levison et al. 2008; Li et al. 2008; Batygin et al. 2011), we also test the dynamically cold and hot samples separately to identify whether a trend might be present in one population and

¹⁶ Whenever we discuss apparent and absolute magnitudes for our sample objects, those magnitudes are measured/calculated from our light curves observations, as these are more accurate than the discovery magnitudes reported by OSSOS.

Figure 2. Absolutely calibrated photometry of our TNO sample. Objects 0–13, ordered by their average magnitude.

Figure 3. Absolutely calibrated photometry of our TNO sample. Objects 14–27, ordered by their average magnitude.

Figure 4. Absolutely calibrated photometry of our TNO sample. Objects 28–41, ordered by their average magnitude.

Figure 5. Absolutely calibrated photometry of our TNO sample. Objects 42–55, ordered by their average magnitude.

Figure 6. Absolutely calibrated photometry of our TNO sample. Objects 56–64, ordered by their average magnitude.

not in the other. In this work, we use the term “hot population” to refer to all of the dynamically excited populations combined (as done in Fraser et al. 2014, and others); specifically our hot population sample contains everything nonclassical plus classical objects with $i \geq 6^\circ$. Our “cold classicals” sample consists only of classicals with $i \leq 4^\circ$. Classicals with $4^\circ < i < 6^\circ$ (two objects in our sample) are excluded from either sample to minimize contamination. The correlation values as well as their significance levels can be found in Table 4 and are simply summarized here. For our samples of 26 cold classical TNOs and 35 hot TNOs, we find that both have similar correlation coefficients to the full sample for the amplitude versus H_r , but with a lower significance than in the full sample (likely due mostly to the now smaller sample sizes). For the amplitude versus inclination, we find that neither population has a statistically significant correlation, just as in the overall sample. Because the semimajor axis (a) is possibly

related to where objects formed, we also tested for correlations between the light-curve variation and a for the full sample and the hot population (the cold population was not tested due to its narrow a range). We find that the semimajor axis is not at all correlated with the variability in the full sample nor in the hot population.

To further test the notion that different populations may have different amplitude distributions, the two-sample Anderson–Darling test was used to compare subsamples. The subsamples used were the classical, resonant, and hot and cold populations. We did not look at the scattering and detached objects in this analysis because the sample sizes are too small for any meaningful results. In every case, the subsample was tested against the remainder of the sample (i.e., classicals versus everything nonclassical, etc.). See Table 5 for the resultant P values. No subsample was found to be significantly different from the rest of the sample.

Figure 7. Left and bottom sides: histograms of H_r magnitude, semimajor axis a , inclination i , Δ_{mag} , and σ_{mag} of our data. Center and top right: scatter plots of these parameters. Classical TNOs are shown in orange, and nonclassical objects are shown in blue.

Table 4
Spearman Rank Correlation Test Results

Parameter	$\rho_{\Delta_{\text{mag}}}$	$P_{\Delta_{\text{mag}}}$	$\rho_{\sigma_{\text{mag}}}$	$P_{\sigma_{\text{mag}}}$
All objects				
H_r	$0.37^{+0.03}_{-0.03}$	0.003	$0.31^{+0.03}_{-0.02}$	0.013
a	$0.10^{+0.03}_{-0.03}$	0.43	$0.11^{+0.02}_{-0.02}$	0.41
i	$-0.05^{+0.03}_{-0.03}$	0.7	$-0.07^{+0.02}_{-0.02}$	0.60
Cold classicals				
H_r	$0.43^{+0.04}_{-0.05}$	0.029	$0.30^{+0.03}_{-0.04}$	0.14
i	$0.25^{+0.05}_{-0.05}$	0.21	$0.38^{+0.03}_{-0.04}$	0.06
Hot populations				
H_r	$0.42^{+0.04}_{-0.05}$	0.013	$0.41^{+0.03}_{-0.04}$	0.015
a	$0.04^{+0.05}_{-0.05}$	0.79	$0.04^{+0.04}_{-0.04}$	0.79
i	$0.08^{+0.05}_{-0.04}$	0.6	$0.03^{+0.03}_{-0.03}$	0.85

Note. Tests for correlation between the measured light-curve variation Δ_{mag} and σ_{mag} and the parameter listed in the first column.

4.2. Period Analysis

The rotation periods of TNOs range from 3.9 hr (Haumea) to 154 hr (Pluto), with a mean of 7–9 hr (Duffard et al. 2009; Benecchi & Sheppard 2013; Thirouin et al. 2016); there are clearly a number of assumptions and biases that go into this mean,

Table 5
Two-sample Anderson–Darling Test Results

Subpopulation	N_{obj}	$P_{\Delta_{\text{mag}}}$	$P_{\sigma_{\text{mag}}}$
Classicals	37	$0.15^{+0.10}_{-0.07}$	$0.11^{+0.06}_{-0.05}$
Resonant	15	0.8 ± 0.2	$0.76^{+0.12}_{-0.14}$
Hot	35	$0.13^{+0.09}_{-0.06}$	$0.09^{+0.06}_{-0.03}$
Cold	26	0.4 ± 0.2	$0.29^{+0.12}_{-0.09}$

Note. Tests for whether two samples are likely to have been drawn from the same source population. Here we test whether the light-curve variability (measured by Δ_{mag} and σ_{mag}) distribution is different for different dynamical subpopulations. In every case here, a subsample is tested against the remainder of our sample (e.g., the resonant objects against everything that is not resonant).

not the least of which is the aliasing effects from observations on consecutive nights and the fact that tracking low-amplitude and slowly varying objects requires significant telescope time. Both of these biases exist in our data set; nevertheless, we seek to use the data we present here to at least place limits on the rotation periods and amplitudes of the objects in our sample. In the few cases where our data allow for more extensive interpretation, we proceed as appropriate for each object. We attempt to fit periods to our light-curve data using two methods: a phase dispersion minimization (PDM) method and a power spectral density (PSD)

Table 6
Best Periods from Two Methods, in Hours

Object	Period _{PDM} (hour)		Period _{PSD} (hour)	
2013 UL ₁₅	11.76 ± 0.02	(41.3%)	11.80 ± 0.03	(100.0%)
2013 UC ₁₈	15.66 ± 0.23	(80.7%)	15.70 ± 0.08	(68.8%)
2013 UP ₁₅	16.02 ± 0.09	(37.7%)	16.00 ± 0.07	(100.0%)
2013 UM ₁₅	6.44 ± 0.03	(81.0%)	6.40 ± 0.04	(49.0%)
2013 UN ₁₅	20.30 ± 0.08	(79.2%)	20.30 ± 0.09	(43.6%)
2015 RU ₂₇₇	6.58 ± 0.05	(84.4%)	6.50 ± 0.03	(99.3%)
2015 RG ₂₈₁	6.03 ± 0.02	(98.2%)	6.07 ± 0.04	(54.3%)
2015 RV ₂₇₈	13.54 ± 0.04	(94.8%)	13.70 ± 0.14	(74.9%)
2015 RU ₂₇₉	14.38 ± 0.08	(74.0%)	14.40 ± 0.09	(41.3%)
2015 RT ₂₇₉	11.34 ± 0.11	(30.3%)	11.30 ± 0.09	(71.9%)
2003 SP ₃₁₇	12.45 ± 0.04	(100.0%)	12.45 ± 0.04	(100.0%)
2015 RA ₂₈₀	12.66 ± 0.05	(99.7%)	12.72 ± 0.04	(100.0%)

Note. Numbers in parentheses are the percentage of resampled light curves that had a “best” period within 5σ of the reported value. Only objects where the two methods agree on the best period are included. As these objects are small, their variability is most likely shape-dominated; shape dominated light curves have two peaks per rotation of the object. These periods have thus been doubled to represent the rotation period of the object.

(This table is available in machine-readable form.)

method. Because our TNOs are all small enough that we do not expect them to be spherical, they should all have double-peaked periods. The two light-curve peaks of an elongated TNO are often difficult to distinguish (for a perfectly symmetrical ellipsoid, the two peaks would be identical). These methods, therefore, simply identify the period of the light curve, not the TNO. We double the single-peaked periods found by our two period methods to get the most likely rotation period of the TNO.

Because our observing window is about 30 hr (from the start of night one to the end of night two), we are able to sample rotation periods from the rotational break-up-limit of 3.3 hr (Romanishin & Tegler 1999) to about 60 hr (where we sample half a rotation, which is a full peak-to-peak cycle for a double-peaked light curve). For the PSD method, we, therefore, fold the light curves using every period from 1.0 to 30.0 hr in 0.1 hr intervals. The Fourier coefficients are calculated from each folded light curve; the sum of the squares of the Fourier coefficients as a function of the period is the PSD. The period that has the highest PSD value is selected as the most likely period of the TNO. In the PDM method, we fit the data points for each object using a modified PDM (Stellingwerf 1978; Buie et al. 2018). This method goes through every possible period, folds the data, and fits a second-order Fourier series to each folded light curve. The quality of each fit is captured from the residuals; the fits are ranked and the fit with the highest quality is selected.

Table 6 lists the periods found from these two methods (converted into double-peak periods) for objects where the two methods agree; Figure 8 shows the light curves folded at those periods. When the two methods do not agree, it is likely evidence that we do not have enough data to determine the period with confidence. The PDM curves from our period analysis are available in the extended Figure 10. Although the mean period from our data set analysis is somewhat greater than that given in the literature (~ 12.3 hr compared with 7–9 hr; Duffard et al. 2009; Thirouin et al. 2010; Benecchi & Sheppard 2013), it is important to recognize that the periods we are reporting are based on single epoch measurements without the same fidelity of many of the light curves in the literature. The literature contains both single- and

double-peaked light curves and light curves of binary objects. We cannot distinguish among these interpretations and have assumed a double-peaked light curve for all objects, so one should not overinterpret this apparent result from our data set. This sample of 12 periods is insufficient to draw any conclusions, other than the fact that we would need a larger baseline than two consecutive 6 hr nights to determine the period of a larger fraction of objects. Adding a third night and observing closer to opposition (when the targets are visible for 8 hr) would allow determination of periods for a much larger fraction of light curves. We, therefore, leave discussions of the period distribution for future work.

5. Discussion and Conclusions

5.1. Implications for Large Surveys

Large variability can have an influence on whether or not an object is discovered in a magnitude-limited survey. Most large surveys use an automated moving object pipeline to find TNO candidates. For the Canada–France Ecliptic Plane Survey (Kavelaars et al. 2009; Petit et al. 2011), OSSOS, and the Alexandersen et al. (2016) survey, TNOs were identified using three discovery images with one hour between each. Nonstationary sources within three images of a field are linked together as a candidate TNO detection; various constraints on the rate, angle, and linearity of motion are imposed, as well as a requirement of similar magnitudes, in order to limit the number of false candidates. If a TNO’s magnitude is highly variable, this might leave it undetected, either because it might be too faint to be detected in one of the three images or, if the constraints in the detection pipeline are too tight, because the pipeline might not consider the three points to be the same object because it has different magnitudes.

In our sample of 63 TNO light curves (most with observations on both nights), we find that only 6 ± 1 have a $\Delta_{\text{mag}} < 0.2$ mag, while 31 ± 2 (just under half the sample) have a $\Delta_{\text{mag}} > 0.4$ mag, and 11 ± 1 have $\Delta_{\text{mag}} > 0.6$ mag.¹⁷ However, those variations are usually over many hours. In order to evaluate the impact that light-curve variation could have on shorter timescales, we measured the typical variation on 1–2 hr timescales. Since our images for these light curves are typically spaced 36 minutes apart, we calculated the Δ_{mag} for all 1.25 hr (3 images), 1.85 hr (4 images) and 2.45 hr (5 images) subsets of our light curves. We find that in 1.25 hr, the median value of the Δ_{mag} is 0.13 mag and the standard deviation of the Δ_{mag} distribution is 0.12 mag. For 1.85 hr, the median and standard deviation are 0.16 and 0.13, respectively, while for 2.45 hr they are 0.19 and 0.14 mag, respectively. Figure 9 shows the Δ_{mag} distribution within these three time spans. The moving object pipeline used for the Alexandersen et al. (2016) survey and for OSSOS only had the weak constraint that the faintest and brightest points within the three discovery images (spaced about 1 hr apart) had to have a flux ratio of less than 4, which corresponds to a magnitude difference of about 1.5 mag. In our data from this work, we never see variability greater than 1.2 mag within a 2 hr window; therefore, it seems highly unlikely that a real objects was rejected by the detection pipeline due to natural variability. Because the overall average variability seen within our data is much larger than the average variability measured within 1.25–2.45 hr, this demonstrates the

¹⁷ The uncertainties quoted in this sentence on the number of objects come from resampling the light-curve photometry 1000 times and calculating the values for each resampled set.

Figure 8. Folded light curves for the 12 objects for which we have a period estimate. Blue and orange points show data from the first and second nights, respectively. The arbitrary phase = 0 point was chosen such that the brightest measured magnitude falls at phase = 0.5. The exact values of the MJD, magnitude, and uncertainty of all observations can be found in Table 3.

perhaps obvious point that the average magnitude measured within a few hours is not an accurate measurement of the true average magnitude of the TNO. Discovery images from surveys like CFPS, OSSOS, and the Alexandersen et al. (2016) survey all depend on measuring the magnitude in three discovery images; the fact that these measured magnitudes are potentially several tenths of a magnitude from the true average magnitude should be included when performing survey simulations and model analyses.

Variability is important to consider when measuring photometric colors of TNOs as well. Because most facilities do not have

the ability to observe in multiple bandpasses simultaneously, the images in different filters must be taken in sequence. If the object is faint and thus requires a long exposure time in some/each filter, its variability could cause an erroneous measurement of the color if the brightness varies significantly within the timespan of the observations. For accurate photometric colors, it is, therefore, important to account for light-curve variability, except in cases of very short (thus, nearly simultaneous) exposure sequences for bright objects. This can be done by repeating observations of the filter that requires least exposure time several times during a sequence (for example, $r-g-r-J-r$), as has become common

Figure 9. Cumulative distribution of the magnitude variation (the maximum minus the minimum: Δ_{mag}) within 1.25 hr (blue, top), 1.85 hr (orange, middle), and 2.45 hr (green, bottom) sections of light curves.

practice, to get a rough idea of the light-curve variation during the sequence. Alternatively, if some of the filters require enough exposure time to warrant multiple exposures, those exposures should be spread out in the sequence (for example, the $r-g-J-g-r$ sequence used by Bannister et al. 2017). Of course, this relies on having fast filter changes and can, therefore, not be done with HSC, which has a filter exchange time of about 30 minutes. It should be obvious that photometry acquired on different days cannot be used to calculate reliable colors unless the light curve is known, so TNO colors reported from surveys like the HSC Subaru Strategic Program (HSC SSP; Aihara et al. 2018; Terai et al. 2018) or the LSST survey should be seen as very rough color estimates with a likely uncertainty of ~ 0.2 mag.

Expected to start science operations in 2022, LSST will provide an inventory of the trans-Neptunian region down to a 5σ limiting magnitude of approximately 24.6 in r and 24.8 in g (LSST Science Collaboration et al. 2009; Ivezić et al. 2019). LSST is expected to discover over 40,000 TNOs during its planned 10 years of science operations (LSST Science Collaboration et al. 2009). During this period, TNOs within the survey footprint will be imaged hundreds of times by LSST in multiple filters (*ugrizy*), producing sparsely sampled light curves. Our HSC variability study overlaps the size and magnitude range that LSST will be sensitive to. Thus, the variability we observe can be taken as a minimum value for the variability LSST will see for its TNO sample. Over a few hr baseline, 90% of our HSC sample vary in brightness up to 0.4 mag. This is more variability than shallower past wide-field solar system surveys had to deal with. As detailed above, OSSOS, which our sample is derived from, had no significant brightness/variability constraints when identifying moving objects (Bannister et al. 2018). This may be important in the development of the LSST moving object detection pipeline and for consideration when assessing the TNO detection completeness for LSST. Additionally, in the sparse light curves LSST will produce, objects with more than 0.5 mag variation can potentially be flagged as extreme shapes in need of further higher-cadence follow-up observations.

Finally, we note that objects in this size range do not have enough mass to ensure hydrostatic equilibrium, so the variability seen is, therefore, most likely caused by the objects being highly

nonspherical. Given the correlation between the absolute H_r magnitude and variability shown above, it is unreasonable to expect that even smaller object can be modeled as roughly spherical shapes. A number of surveys have searched for serendipitous stellar occultations by small (diameters ~ 1 km, roughly corresponding to $H_r \sim 16$ –19 depending on albedo) TNOs in order to measure the size distribution of such objects (Roques et al. 2003; Bickerton et al. 2008; Liu et al. 2008; Bianco et al. 2009; Schlichting et al. 2012; Zhang et al. 2013; Lehner et al. 2016). TNOs in this size range are in the Fresnel regime when measuring from the ground at visible wavelengths, and their occultation shadows thus exhibit significant diffraction features (Roques et al. 1987; Nihei et al. 2007). Most survey teams use the approximation of spherical occulting objects in order to simplify the calculation of the occultation event parameters, but when nonspherical shapes are considered, there may be significant effects on the resulting occultation shadows (Roques et al. 1987; Castro-Chacón 2019). Obviously, we did not measure light curves of such small objects in this survey; however, based on our observations of larger ($8 > H_r > 10$) TNOs, we propose that these surveys need to consider the expectation of nonspherical objects when defining event detection criteria, characterizing any occultation events, or estimating any survey detection efficiencies.

5.2. Contact Binaries

To date, in the trans-Neptunian belt, only 2001 QG₂₉₈ has been confirmed as a contact binary (Sheppard & Jewitt 2004; Lacerda et al. 2014) besides the *New Horizons* flyby target 2014 MU₆₉. This confirmation is based on the large light-curve amplitude of $\Delta_{\text{mag}} \geq 0.9$ mag, and the U/V shape at the minimum/maximum of the brightness. However, such a large amplitude is only observed if the two components are seen equator-on (or almost equator-on). If the two components are not aligned with the viewer’s line of sight, the amplitude will be smaller (simple geometry; Lacerda 2011; Lacerda et al. 2014; Thirouin et al. 2017; Thirouin & Sheppard 2017, 2018).

Our sparse light curves reveal no obvious contact binaries, although they do contain candidates that should be observed further. None of the light curves reported here present a definite

full peak-to-peak amplitude larger than 0.9 mag. 2015 RQ₂₈₀, 2015 RS₂₈₁, and 2015 RW₂₈₀ have a Δ_{mag} around 1 mag, but the light curves are too noisy for drawing conclusions. Several objects like 2003 SP₃₁₇, 2015 RB₂₈₀, 2013 UN₁₅, and 2013 SM₁₀₀ display a $\Delta_{\text{mag}} > 0.5$ mag. Unfortunately, because we do not have a full maximum and minimum showing a clear U and V shape, it is difficult to classify them as likely contact binaries. More observations are required in order to confirm whether these objects are contact binaries or simply highly elongated bodies.

5.3. Conclusions

We obtained a large sample of sparse partial light curves of 65 TNOs, most of which are small ($H_r > 7$) and, therefore, fainter than have typically been studied before, with up to 22 observations in acceptable conditions over two nights. While the variability for many of these objects might only be a lower limit because we have not observed the full rotation of the object, we can draw some tentative conclusions. As seen by Benecchi & Sheppard (2013), we confirm that the amplitude of the light curve correlates with the absolute magnitude. However, in contrast, we do not see a statistically significant correlation with the inclination.

We find that a large fraction of our observed TNOs have large brightness variations, even on 1–2 hr timescales. Thirty one objects (just under half the sample) have a $\Delta_{\text{mag}} > 0.4$ mag over the course of our observations, while the median variability within a 1.85 hr timespan was 0.16 mag. TNO variability must be accounted for when simulating/modeling discovery surveys like OSSOS and LSST, as well as when observing nonsimultaneous TNO colors.

In this pilot study, we did not find any significant difference in amplitude distribution between different dynamical classes. However, our sample included very few objects in the scattering and detached classes. Future work should, therefore, target more of these objects in order to have similar sample sizes for each population. We were able to estimate periods for 12 of the 65 TNOs. However, these periods are not certain due to aliasing. In order to estimate periods for a larger fraction of the sample and reduce aliasing effects, a longer baseline of observations is needed.

This paper is based on data collected at the Subaru Telescope and retrieved from the HSC data archive system, which is operated by Subaru Telescope and Astronomy Data Center at National Astronomical Observatory of Japan. The access to Subaru telescope from Taiwan is supported by the Academia Sinica Institute of Astronomy and Astrophysics. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We would also like to acknowledge the maintenance, cleaning, administrative, and support staff at academic and telescope facilities, whose labor maintains the spaces where astrophysical inquiry can flourish.

This work is based on TNO discoveries obtained with MegaPrime/MegaCam, a joint project of the Canada–France–Hawaii Telescope (CFHT) and CEA/DAPNIA, at CFHT, which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. A portion of the access to the CFHT was made possible by the Academia Sinica

Institute of Astronomy and Astrophysics, Taiwan. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency.

M.E.S. was supported by the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Brazil, Canada, Chile, and USA. M.B. acknowledges support from UK STFC grant ST/L000709/1. K.V. acknowledges support from NASA grants NNX14AG93G and NNX15AH59G. S.D.B. acknowledges support by the NASA under Grant/Contract/Agreement No. NNX15AE04G issued through the SSO Planetary Astronomy Program. M.R.E. acknowledges support from the ASIAA summer student program.

This paper makes use of software developed for the Large Synoptic Survey Telescope. We thank the LSST Project for making their code available as free software at <http://dm.lsst.org>. This research has made use of NASA’s Astrophysics Data System Bibliographic Services. This research made use of SciPy (Jones et al. 2001), NumPy (van der Walt et al. 2011), matplotlib (a Python library for publication quality graphics Hunter 2007) and Astropy (a community-developed core Python package for Astronomy Astropy Collaboration et al. 2013; The Astropy Collaboration et al. 2018). This research made use of ds9, a tool for data visualization supported by the Chandra X-ray Science Center (CXC) and the High Energy Astrophysics Science Archive Center (HEASARC) with support from the *James Webb Space Telescope* Mission office at the Space Telescope Science Institute for 3D visualization. IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation (Tody 1993).

The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy Heidelberg, and the Max Planck Institute for Extraterrestrial Physics Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, NASA under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

The acknowledgments were compiled in part using the Astronomy Acknowledgment Generator.

Facilities: Subaru (HSC), PS1.

Software: Python (van Rossum & de Boer 1991), Matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011), SciPy (Jones et al. 2001), TRIPPy (Fraser et al. 2016), Ureka (Hirst et al. 2014), IRAF (Tody 1993), Astropy (Astropy Collaboration et al. 2013; The Astropy Collaboration et al. 2018), SExtractor (Bertin & Arnouts 1996), ds9 Joye & Mandel (2003).

Appendix

The PDM curves from our period analysis are available in the extended Figure 10.

Figure 10. PDM plot from our period analysis. Vertical dashed orange lines show our favored single-peak period for the objects listed in Table 6 and shown in Figure 8. Objects 0–13, ordered by average magnitude shown here. (An extended version of this figure is available.)

ORCID iDs

Mike Alexandersen <https://orcid.org/0000-0003-4143-8589>
 Susan D. Benecchi <https://orcid.org/0000-0001-8821-5927>
 Ying-Tung Chen (英同陳) <https://orcid.org/0000-0001-7244-6069>
 Marielle R. Eduardo <https://orcid.org/0000-0002-0760-1584>
 Audrey Thirouin <https://orcid.org/0000-0002-1506-4248>
 Megan E. Schwamb <https://orcid.org/0000-0003-4365-1455>
 Matthew J. Lehner <https://orcid.org/0000-0003-4077-0985>
 Shiang-Yu Wang (王祥宇) <https://orcid.org/0000-0001-6491-1901>
 Michele T. Bannister <https://orcid.org/0000-0003-3257-4490>
 JJ. Kavelaars <https://orcid.org/0000-0001-7032-5255>
 Jean-Marc Petit <https://orcid.org/0000-0003-0407-2266>
 Kathryn Volk <https://orcid.org/0000-0001-8736-236X>

References

- Aihara, H., Arimoto, N., Armstrong, R., et al. 2018, *PASJ*, **70**, S4
 Alexandersen, M., Gladman, B., Kavelaars, J. J., et al. 2016, *AJ*, **152**, 111
 Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, **558**, A33
 Bannister, M. T., Gladman, B. J., Kavelaars, J. J., et al. 2018, *ApJS*, **236**, 18
 Bannister, M. T., Kavelaars, J. J., Petit, J.-M., et al. 2016, *AJ*, **152**, 70
 Bannister, M. T., Schwamb, M. E., Fraser, W. C., et al. 2017, *ApJL*, **851**, L38
 Batygin, K., Brown, M. E., & Fraser, W. C. 2011, *ApJ*, **738**, 13
 Benecchi, S. D., & Sheppard, S. S. 2013, *AJ*, **145**, 124
 Bertin, E., & Arnouts, S. 1996, *A&AS*, **117**, 393
 Bianco, F. B., Protopapas, P., MacLeod, B. A., et al. 2009, *AJ*, **138**, 568
 Bickerton, S. J., Kavelaars, J. J., & Welch, D. L. 2008, *AJ*, **135**, 1039
 Bosch, J., Armstrong, R., Bickerton, S., et al. 2018, *PASJ*, **70**, S5
 Buie, M. W., Zangari, A. M., Marchi, S., Levison, H. F., & Mottola, S. 2018, *AJ*, **155**, 245
 Castro-Chacón, J. H., Reyes-Ruiz, M., Lehner, M. J., et al. 2019, *PASP*, **131**, 064401
 Duffard, R., Ortiz, J. L., Thirouin, A., Santos-Sanz, P., & Morales, N. 2009, *A&A*, **505**, 1283
 Fraser, W., Alexandersen, M., Schwamb, M. E., et al. 2016, *AJ*, **151**, 158
 Fraser, W. C., & Brown, M. E. 2012, *ApJ*, **749**, 33
 Fraser, W. C., Brown, M. E., Morbidelli, A., Parker, A., & Batygin, K. 2014, *ApJ*, **782**, 100
 Gladman, B., Marsden, B. G., & Vanlaerhoven, C. 2008, in *The Solar System Beyond Neptune*, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 43
 Hahn, J. M., & Malhotra, R. 2005, *AJ*, **130**, 2392
 Hirst, P., Slocum, C., Turner, J., et al. 2014, in *ASP Conf. Ser. 485, Astronomical Data Analysis Software and Systems XXIII*, ed. N. Manset & P. Forshay (San Francisco, CA: ASP), 335
 Hunter, J. D. 2007, *CSE*, **9**, 90
 Ivezić, Z., Kahn, S. M., Tyson, J. A., et al. 2019, *ApJ*, **873**, 111
 Jones, E., Oliphant, T., Peterson, P., et al. 2001, *SciPy: Open Source Scientific Tools for Python v.0.17.1*, <http://www.scipy.org/>
 Joye, W. A., & Mandel, E. 2003, in *ASP Conf. Ser. 295, Astronomical Data Analysis Software and Systems XII*, ed. H. E. Payne, R. I. Jedrzejewski, & R. N. Hook (San Francisco, CA: ASP), 489
 Kaula, W. M., & Newman, W. I. 1992, *AdSpR*, **12**, 3
 Kavelaars, J. J., Jones, R. L., Gladman, B. J., et al. 2009, *AJ*, **137**, 4917
 Kortenkamp, S. J., Malhotra, R., & Michtchenko, T. 2004, *Icar*, **167**, 347
 Lacerda, P. 2011, *AJ*, **142**, 90
 Lacerda, P., McNeill, A., & Peixinho, N. 2014, *MNRAS*, **437**, 3824
 Lawler, S. M., Shankman, C., Kavelaars, J. J., et al. 2018, *AJ*, **155**, 197
 Lehner, M. J., Wang, S.-Y., Reyes-Ruiz, M., et al. 2016, *Proc. SPIE*, **9906**, 99065M
 Levison, H. F., Morbidelli, A., Van Laerhoven, C., Gomes, R., & Tsiganis, K. 2008, *Icar*, **196**, 258
 Li, J., Zhou, L.-Y., & Sun, Y.-S. 2008, *ChA&A*, **32**, 409
 Liu, C.-Y., Chang, H.-K., Liang, J.-S., & King, S.-K. 2008, *MNRAS*, **388**, L44
 LSST Science Collaboration, Abell, P. A., Allison, J., et al. 2009, *LSST Science Book v.2.0*, <https://www.lsst.org/scientists/scibook>
 Lupton, R., Gunn, J. E., Ivezić, Z., Knapp, G. R., & Kent, S. 2001, in *ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X*, ed. F. R. Harnden, Jr., F. A. Primini, & H. E. Payne (San Francisco, CA: ASP), 269
 Magnier, E. A., Schlafly, E., Finkbeiner, D., et al. 2013, *ApJS*, **205**, 20
 Malhotra, R. 1993, *Natur*, **365**, 819
 Malhotra, R. 1995, *AJ*, **110**, 420
 Miyazaki, S., Komiyama, Y., Kawanomoto, S., et al. 2018, *PASJ*, **70**, S1
 Murray-Clay, R. A., & Chiang, E. I. 2005, *ApJ*, **619**, 623
 Nihei, T. C., Lehner, M. J., Bianco, F. B., et al. 2007, *AJ*, **134**, 1596
 Peixinho, N., Doressoundiram, A., Delsanti, A., et al. 2003, *A&A*, **410**, L29
 Petit, J.-M., Kavelaars, J. J., Gladman, B. J., et al. 2011, *AJ*, **142**, 131
 Pike, R. E., Fraser, W. C., Schwamb, M. E., et al. 2017, *AJ*, **154**, 101
 Romanishin, W., & Tegler, S. C. 1999, *Natur*, **398**, 129
 Roques, F., Moncuquet, M., & Sicardy, B. 1987, *AJ*, **93**, 1549
 Roques, F., Moncuquet, M., Lavillonière, N., et al. 2003, *ApJL*, **594**, L63
 Ryan, E. L., Sharkey, B. N. L., & Woodward, C. E. 2017, *AJ*, **153**, 116
 Schlafly, E. F., Finkbeiner, D. P., Jurić, M., et al. 2012, *ApJ*, **756**, 158
 Schlichting, H. E., Ofek, E. O., Sari, R., et al. 2012, *ApJ*, **761**, 150
 Shankman, C., Gladman, B. J., Kaib, N., Kavelaars, J. J., & Petit, J. M. 2013, *ApJL*, **764**, L2
 Sheppard, S. S. 2012, *AJ*, **144**, 169
 Sheppard, S. S., & Jewitt, D. 2004, *AJ*, **127**, 3023
 Sheppard, S. S., Lacerda, P., & Ortiz, J. L. 2008, in *The Solar System Beyond Neptune*, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 129
 Spearman, C. 1904, *Am. J. Psych.*, **15**, 72
 Stellingwerf, R. F. 1978, *ApJ*, **224**, 953
 Tegler, S. C., Romanishin, W., & Consolmagno, G. J., Jr. 2016, *AJ*, **152**, 210
 Terai, T., Yoshida, F., Ohtsuki, K., et al. 2018, *PASJ*, **70**, S40
 The Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, **156**, 123
 Thirouin, A., Noll, K. S., Ortiz, J. L., & Morales, N. 2014, *A&A*, **569**, A3
 Thirouin, A., Ortiz, J. L., Duffard, R., et al. 2010, *A&A*, **522**, A93
 Thirouin, A., & Sheppard, S. S. 2017, *AJ*, **154**, 241
 Thirouin, A., & Sheppard, S. S. 2018, *AJ*, **155**, 248
 Thirouin, A., Sheppard, S. S., Noll, K. S., et al. 2016, *AJ*, **151**, 148
 Thirouin, A., Sheppard, S. S., & Noll, K. S. 2017, *ApJ*, **844**, 135
 Thommes, E. W., Duncan, M. J., & Levison, H. F. 2002, *AJ*, **123**, 2862
 Tody, D. 1993, in *ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II*, ed. R. J. Hanisch, R. J. V. Brissenden, & J. Barnes (San Francisco, CA: ASP), 173
 Tonry, J. L., Stubbs, C. W., Lykke, K. R., et al. 2012, *ApJ*, **750**, 99
 Trujillo, C. A., & Brown, M. E. 2002, *ApJL*, **566**, L125
 Tsiganis, K., Gomes, R., Morbidelli, A., & Levison, H. F. 2005, *Natur*, **435**, 459
 van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, *CSE*, **13**, 22
 van Rossum, G., & de Boer, J. 1991, *Proc. Spring 1991 EurOpen Conf., EurOpen: UNIX Distributed Open Systems in Perspective* (Buntingford: EurOpen), 229
 Zhang, Z.-W., Lehner, M. J., Wang, J.-H., et al. 2013, *AJ*, **146**, 14