LIGHT CURVES OF 32 LARGE TRANSNEPTUNIAN OBJECTS

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Abstract

We present observations of 32 primarily bright, newly discovered Transneptunian objects (TNOs) observable from the Southern Hemisphere during 39 nights of observation with the Irénée du Pont 2.5 m telescope at Las Campanas Observatory. Our dataset includes objects in all dynamical classes, but is weighted toward scattered objects. We find 15 objects for which we can fit periods and amplitudes to the data, and place light curve amplitude upper limits on the other 17 objects. Combining our sample with the larger light curve sample in the literature, we find a 3σ correlation between light curve amplitude and absolute magnitude with fainter objects having larger light curve amplitudes. We looked for correlations between light curve and individual orbital properties, but did not find any statistically significant results. However, if we consider light curve properties with respect to object dynamical classification, we find statistically different distributions between the classical-scattered and classical-resonant populations at the 95.60% and 94.64% level, respectively, with the classical objects having larger amplitude light curves. The significance is 97.05% if the scattered and resonant populations are combined. The properties of binary light curves are largely consistent with the greater TNO population except in the case of tidally locked systems. All the Haumea family objects measured so far have light curve amplitudes and rotation periods <10 hr, suggesting that they are not significantly different from the larger TNO population. We expect multiple factors are influencing object rotations: object size dominates light curve properties except in the case of tidal, or proportionally large collisional interactions with other TNOs, the influence of the latter being different for each TNO sub-population. We also present phase curves and colors for some of our objects.

Key words: Kuiper belt: general – surveys

Online-only material: color figures, figure set, machine-readable and VO tables

1. INTRODUCTION

With discovery of the first Transneptunian object (TNO) in 1992 (Jewitt et al. 1993) a new area of study on small bodies in our solar system was opened. Most of these objects are located in the Kuiper Belt beyond the orbit of Neptune. The dynamically unstable Centaurs are found between the orbits of Jupiter and Neptune. More than 1600 of an expected 105 objects (larger than ~100 km; Petit et al. 2011) have been observed and recorded in the Minor Planet Center (MPC) database. Of these, about half have orbits with small enough uncertainties to be observed from typical ground-based telescope facilities. Within the TNO population as a whole, objects are clustered in identifiable dynamical locations with respect to their interaction, or lack of interaction, with Neptune, or in areas near the plane of the solar system (Elliot et al. 2005; Lykawka & Mukai 2007; Gladman et al. 2008). In this paper we use the classification system defined by the Deep Ecliptic Survey (DES; Elliot et al. 2005) and for statistical purposes combine objects in scattered orbits as described. In short, cold classical objects are TNOs with low eccentricity, circular orbits, inclinations less than 5°–12° (Noll et al. 2008b; Elliot et al. 2005; Peixinho et al. 2008; for the statistical analyses in this paper we use 5°:5), and no previously traced interaction with Neptune. Resonance objects are in mean-motion resonances with Neptune. Scattered objects consist of Centaurs (objects with orbits inside of Neptune), scattered disk objects (objects with large inclinations and eccentricities, with perihelia beyond 30 AU that are not resonant or cold classical objects), and detached objects (objects with moderate to high eccentricities whose perihelia are sufficiently far (>40 AU) from Neptune so they are not influenced by Neptune). Because of our broad grouping of objects for statistical analysis, the distinctions between the three classification systems is not significant.

The photometric variability of a TNO versus time, its light curve, is a powerful tool for learning about the shapes and surface features of these distant objects. Light curve amplitude, rotation period, color dependence, and shapes of light curves are all affected by the details the TNO’s physical properties. The spin state of these bodies is important because it records the history of collisional and other evolutionary processes acting in the Kuiper Belt over time and at the extremes, can provide constraints on the material properties (and interior structure) of these objects. Disruption lifetimes for the largest objects (d ≳ 400 km) are longer than the age of the solar system, so we expect that the rotations of these objects are the results of impacts during the formation era of the Kuiper Belt (Lacerda 2005). Objects with d ∼ 200 km have probably avoided catastrophic break-up, although their rotations could be modified by more recent collisions (Davis & Farinella 1997). The smallest objects (d ≲ 100 km) are likely fragments resultant from multiple collisions over the age of the solar system (Catullo et al. 1984; Lacerda 2005; see Campo & Benavidez 2012 for a review of the collisional environment spanning the range of TNO sizes). Likewise, TNO shape is also thought to be related to object size, with the largest objects being dominated by self-gravity and the smallest objects being collisional fragments without significant self-gravity influence.
In this paper we present light curve work carried out on 32 bright TNOs accessible from Las Campanas Observatory. Most of the objects in our target list were discovered as part of recent large area surveys conducted for bright outer solar system objects in the Southern Hemisphere (Sheppard et al. 2011; Rabinowitz et al. 2012). Other objects were selected from newly discovered TNOs in the MPC database with the requirement that they have absolute magnitudes, $H_V$, brighter than $\sim 5.6$ (corresponding to a size of $d \sim 330$ km assuming an albedo of 0.1). We also observed binaries bright enough for our telescope-instrument combination ($m_R < 23.0$). The survey includes five binaries and four Haumea family objects.

2. OBSERVATIONS

Observations were made using the Irèneé du Pont 2.5 m telescope at the Las Campanas Observatory during a series of eight 3–6 night runs (in 2007 and 2011–2012, Table 1). Images were collected using the direct CCD camera, a SITe2K chip with a pixel scale of 0′′.259 pixel$^{-1}$ and a field of view of 8.85 square arcmin. The data were collected in pairs or triplets for 300 s in duration per exposure using the entire array and reading the chip in “fast” mode with a readout time of $\sim 67$ s. Observations for each TNO were collected on multiple nights within a single run with approximately 45–75 minute spacing between visits. The runs were scheduled in pairs four to eight weeks apart so that light curve periods could be de-aliased from the 24 hr observing cycle within an observing run. Light curve data were collected using both the Sloan $r'$ and Bessel $R$ (Kron-Cousins equivalent) filters. Individual images have S/N of $\geq 30$ (uncertainties $< 0.03$ mag), depending on the TNO magnitude and observing conditions. Photometric standard star data for overlapping stars from the Landolt (1992) and Sloan (Smith et al. 2002) surveys with TNO-like colors [104_428, 113_260, 113_339, RU_149B, and RU_149F] were collected during photometric nights. We also collected colors for some of the TNOs during one photometric night of observation bracketing the Sloan $g'$ and Sloan $i'$ measurements with the $r$-band light curve filter (e.g. Sloan $r' - \text{Sloan } g' - \text{Sloan } r'$) to ensure that variations did not unknowingly influence the colors. The conditions for each night are listed in Table 1.

3. DATA ANALYSIS

For each run, a set of master biases, twilight sky flats, and dome flats were generated to calibrate the data using standard routines from Dr. Marc Buie’s IDL libraries (http://www.boulder.swri.edu/~buie/IDL/). The data was flattened using sky flats for pointings with hour angles less than or equal to 1.0 hr east, and using dome flats for pointings with hour angles greater than 1 hr east; this crossover point was empirically determined to provide the most consistent sky backgrounds across the chip. Each image was evaluated and the position of the TNO was identified by eye. Likewise, astrometry was carried out on each image, and on each star in the image with a peak pixel count $< 50,000$ (the saturation level for the detector). For each object, three astrometric measurements (the first, last, and carried out on the TNO) were submitted to the MPC. Large ($\sim 4$ times the FWHM) and small ($\sim$FWHM) aperture photometry was carried out on all the stars identified on the image and saved to a file. Small aperture photometry was carried out on the TNO.

The star list was then culled in the following way to find the best comparison stars for each TNO: (1) the star was identified on each night of a single run, (2) the star was bright compared to the TNO (typically $3$–$4$ mag brighter than the TNO and with a peak pixel between 20,000–30,000 counts, well below the nonlinear regime of the detector), (3) when plotted versus time the star had no significant variations (the star was differentiated by a selection of other stars of similar magnitude on the field to account for airmass and sky fluctuations, if the resulting difference varied by less than $3\sigma$ it was considered useable), and (4) the star was located relatively close to the TNO on the chip on at least one night of observation. After 10–15 comparison stars were identified each was evaluated by eye to ensure that it was not contaminated by a background source or itself a galaxy, typically a few of the stars were thrown out. Since TNOs move during the night relative to the background field stars these images were also examined versus time to look for potential background contaminates. Images with background contamination due to faint galaxies, or nearby stars were eliminated. Most of the TNOs were in average density star fields, with the TNOs moving through clear areas, so few images were excluded (the fields were pre-selected as much as possible to avoid background object overlaps so this issue affects $\leq$5% of the data).

The selected field stars were photometrically calibrated using the standard star observations. If the sky was photometric for multiple nights in a given run, the calibrated star magnitudes were averaged across all the nights the field was observed. The scatter in the calibrated magnitudes was comparable to the photometric precision of the data and the calibrated magnitude uncertainties were small compared to the uncertainties on the TNO measurements themselves. To minimize uncertainties on the TNO photometry, the small aperture TNO magnitude for each frame was aperture corrected (Howell 2006) with the selected small and large aperture field star magnitudes. Finally, the TNO magnitude was calibrated with a magnitude calibrated field star. For data collected in the Bessel $R$ filter we apply a magnitude transformation of $+0.202$ mag as determined using the synphot routine$^1$ in IRAF (Laidler et al. 2008) so that all values are based in the Sloan $r'$ system.

In order to combine data across runs, the TNO magnitudes were geometrically corrected to unit distance from the Sun ($r$) and Earth ($\Delta$) using the formalism $H_V(\alpha) = R_{\text{obs}}(\alpha) - 5 \log(r\Delta)$, where $\alpha$ is the phase angle of the observation and $R_{\text{obs}}$ is the observed Sloan $r'$ magnitude. In principle, one would also want to correct the magnitudes to a phase angle of $0^\circ$, however, phase curves have not been measured for the majority of our objects and more than half of our objects span $< 0.3$ in phase angle difference between measurements. However, for a few objects when we plotted all the data (magnitude versus time) for that object, we noticed some large-ish ($0.2–0.3$ mag) offsets from earlier runs which observed the same objects (primarily data from the 2012 May dataset which was collected under constantly varying conditions); some of these offsets we thought could be explained by geometry, others could not. Therefore, we period-fit our data considering three different magnitude calculations: (1) geometric correction excluding the phase coefficient as expressed earlier in this paragraph, (2) applying the Bowell et al. (1989) formalism whose

$^1$ In synphot, we use the Kurucz solar model as our reference standard and a reddening function (ebmv) of 0.1 which corresponds to a color term of $\sim 0.55$ mag in V–R (Bencicchi et al. 2011).
Table 1

| du Pont Run Details |
|----------------------|
| Run Dates (UT) | Observing Conditions | Filter | Objects Observed |
| 2007 Jul 15 | Photometric | Bessel R | 119951, 120178, 120347, 145452, 145453, 174567, 307251, 2007 JH43 |
| 2007 Jul 16 | Photometric | | |
| 2007 Jul 17 | Photometric | | |
| 2007 Jul 18 | Photometric | | |
| 2007 Jul 19 | Photometric | | |
| 2007 Jul 20 | Photometric | | |
| 2007 Aug 15 | Photometric | Bessel R | 120178, 307251, 119951, 145453 |
| 2007 Aug 16 | Photometric | | |
| 2007 Aug 17 | Photometric | | |
| 2011 Mar 9 | Photometric | Sloan r‘ | 79360, 278361, 312645, 2010 ER65, 2010 ET65, 2010 FX66, 2010 EK139, 2010 EL139 |
| 2011 Mar 10 | Photometric | | |
| 2011 Mar 11 | Photometric | | |
| 2011 Mar 12 | Photometric | | |
| 2011 Mar 13 | Photometric | | |
| 2011 Mar 31 | Photometric | Sloan r‘ | 278361, 312645, 2007 JF43, 2010 ER65, 2010 FX66, 2010 EK139, 2010 EL139 |
| 2011 Apr 2 | Photometric | | |
| 2011 Apr 3 | Photometric | | |
| 2011 Apr 4 | Photometric | | |
| 2011 Apr 5 | Photometric | | |
| 2011 Sep 28 | Photometric | Sloan r‘ | 225088, 2009 YE7, 2008 QY40, 2010 RF43, 2005 QU182, 2010 VK201 |
| 2011 Sep 29 | Photometric | | |
| 2011 Sep 30 | Photometric | | |
| 2011 Oct 1 | Photometric | | |
| 2011 Oct 2 | Photometric | | |
| 2011 Oct 20 | Photometric | Sloan r‘ | 225088, 303712, 2008 QY40, 2010 RF43, 2010 RO64, 2010 TY53, 2010 VZ98, 2005 QU182, 2010 VK201 |
| 2011 Oct 21 | Photometric | | |
| 2011 Oct 22 | Photometric | | |
| 2011 Oct 23 | Clouds, high wind | | |
| 2011 Oct 24 | Clouds, high wind | | |
| 2012 Mar 18 | Photometric | Bessel R | 79360, 278361, 312645, 2007 JH43, 2010 ET65, 2010 FX66, 2010 EK139, 2010 KZ90, 2005 EF298 |
| 2012 Mar 19 | Photometric | | |
| 2012 Mar 20 | Photometric | | |
| 2012 Mar 21 | Photometric | | |
| 2012 Mar 22 | Photometric | | |
| 2012 May 13 | Variable thick clouds | Sloan r‘ | 2007 JF43, 2007 JH43, 278361, 2010 ER65, 2010 ET65, 2010 FX66, 2010 PU75 |
| 2012 May 14 | High winds | | |
| 2012 May 15 | High winds | | |
| 2012 May 16 | Photometric, high winds | | |
| 2012 May 18 | Clouds by night end | | |

Object Classification Summary

| Classification | Number of Objects in Our Sample | Notes |
|----------------|-------------------------------|-------|
| Cold classical | 4 | All but one is binarya |
| Resonant | 7 | |
| Scattered | 17 | Inclusive of Centaurs; 4 Haumea Familyb |

Notes.

a Noll et al. 2006; Stephens & Noll 2006; Noll et al. 2008c; Noll et al. 2011.
b Ragozzine & Brown 2007; Trujillo et al. 2011.

equations are given in the table note of Table 2, and (3) normalizing the values on each night by the mean magnitude of the object.

4. LIGHT CURVE RESULTS

4.1 Analysis

Table 2 provides detailed observational and geometric circumstances for each TNO on each night of observation; the full table is provided electronically. It records the mid-time (in both calendar format and JD) of the observations, the magnitude range of the observations, the number of observations, the duration of time (hr) covered by the observations, heliocentric distance (AU), geocentric distance (AU), phase angle (°), light time (s) and two magnitudes (Hr, Bowell which uses the Bowell et al. 1989 formalism and Hr′, the reduced magnitude uncorrected for phase angle) for each object, each night. Table 3 provides basic characteristic information about each object and a summary of our light curve conclusions from all of
our observations combined. We ran the dataset for each object through a set of periodogram analyses (described in the following paragraph), for periods ranging from 3 to 20 hr based on our observing windows and aliasing considerations. Some of the resulting phasing or suggested periods were not statistically significant, and instead of making a “best guess” which might be carried forward in the literature incorrectly, we choose instead to place an upper limit on the amplitude of a possible light curve for the duration of a single night of observation (≤8 hr) by averaging the range on all nights of observation. Individual uncertainties on the measurements are ~0.03 mag or better. Individual measurements and plots of the data versus time on each night of observation can be found in online Figures 1.1–1.32. We include in Table 4 and Figure 1 samples of the online data table and figures which include values for all our objects, regardless if they resulted in conclusive period fits, or flat light curves.

For objects with data to which we can fit periods with statistically significant results, we present in Figure 2 the Lomb–Scargle periodogram (top; Scargle et al. 1982) and the data phased to the most significant period assuming single- (middle) and double- (bottom) peaked light curve interpretations. For each dataset we calculate the 99.9% confidence level using the methods described by Horne & Baliunas (1986) and plot the result as a dashed line on each of the periodogram plots. Very similar results are found when using the phase-dispersed minimization (PDM; Stellingwerf 1978) and Harris–Foster (Harris et al. 1989; Foster 1995) fitting techniques. For objects with multiple peaks above the confidence interval we phased the data to each possible period for evaluation, but in all cases the resulting period was the one with the highest Lomb-normalized spectral power value. We list in the notes column of Table 3 possible additional periods that could fit the data (that we were unable to completely rule out), although we run all further analyses with our preferred periods, listed in the specified period column. We fit all three sets of magnitude calculations for each object. We draw our conclusions based on the night normalized data which minimizes any offsets between runs, although it could introduce a bias against objects observed for short periods of time with long period >8 hr rotation curves. Fits on the non-phase-corrected and Bowell-corrected values were also carried out and, where offsets were not an issue, the same periods were identified. Offsets were on order 0.1–0.2 mag, which are within the range of what one would expect for phase corrections. However, we did not sample a complete range of phases for all our objects, only for some objects (see Section 6). For consistency we analyze all the light curves using the night normalized data.

Figure 1. Sample of online plot for each object on each night, in this case for 2005 EF298. The y-axis is the calculated $H_r\,(\alpha)$ magnitude of the object and the x-axis is time in hours referenced to the first observation for this object. The title of each plot is the name of the object and the UT time of the first data point on each individual night of observation.

(The complete figure set (32 images) is available in the online journal.)

Table 2

| Object | Calendar Datea | JDb (mid-time) | $\Delta N_{\text{obs}}$ | $\Delta \theta$ (hr) | $r$ (AU) | $\Delta$ (AU) | $\alpha$ (°) | L-Time (s) | $H_{r, \text{Bowell}}^{4}$ | $H_{r, \text{(α)}}^{4}$ |
|--------|----------------|---------------|------------------------|---------------------|-----------|-------------|-----------|-----------|----------------|----------------|
| 79560  | 2011 Mar 02.09829 | 2455629.58743 | 0.12                   | 8                   | 2.57      | 43.501      | 42.704    | 0.786     | 355.152        | 5.10           | 5.23        |
| 79560  | 2011 Mar 11 0.70889 | 2455631.57120 | 0.18                   | 6                   | 4.44      | 43.501      | 42.735    | 0.841     | 355.413        | 5.11           | 5.25        |
| 79560  | 2011 Mar 11 0.70889 | 2455632.55081 | 0.18                   | 6                   | 4.44      | 43.501      | 42.735    | 0.841     | 355.413        | 5.11           | 5.25        |
| 79560  | 2011 Mar 02.09829 | 2455629.58743 | 0.12                   | 8                   | 2.57      | 43.501      | 42.704    | 0.786     | 355.152        | 5.10           | 5.23        |
| 79560  | 2011 Mar 02.09829 | 2455629.58743 | 0.12                   | 8                   | 2.57      | 43.501      | 42.704    | 0.786     | 355.152        | 5.10           | 5.23        |
Two of the objects with the largest variations are unresolved cold... 120178 2003OP 32 SD 27.02 3.82 Using the DES classification system. This can be found for each object at... b The mean heliocentric inclination based on a 10 My integration of the orbit of the object; used for identifying an object as cold classical. a Using the formalism of Elliot et al. (2005): CL 79360 1997CS 29 CL 3.84 5.09 ± 0.09 2007JH 43 SD 13.45 4.17 ± 0.20 6.04/12.09 0.13 ± 0.02 ... 4.83/9.66 303712 2005PR 21 CL 2.69 5.96 ± 0.02 ... <0.28 6 303775 2005QU 182 SD 12.82 3.36 ± 0.05 9.61/19.22 0.12 ± 0.02 ... ... 305543 2008QY 40 SD 24.02 5.19 ± 0.06 ... <0.15 4 ... 307251 2002KW 14 SD 8.48 5.50 ± 0.03 6.63/13.25 0.25 ± 0.03 ... 5 5.23/10.46 312645 2010EF 35 CL 2.1 19.32 5.23 ± 0.15 7.48/14.97 0.17 ± 0.03 ... 7 5.77/11.54; 8.45/16.90 ... ... 2005EF 298 CL 1.60 5.73 ± 0.05 4.82/9.65 0.31 ± 0.04 ... 3 ... ... 2006JH 23 CL 3.2 15.62 5.92 ± 0.03 ... <0.13 4 ... ... 2007JF 43 CL 3.2 14.90 5.24 ± 0.05 4.76/9.42 0.22 ± 0.02 ... 4 ... ... 2007JH 33 SD 15.09 4.49 ± 0.05 ... <0.08 6 ... ... 2009YE 7 SD 28.00 4.26 ± 0.01 ... <0.20 4 Haumea, multiple periods ... 2010EK 139 7.2 29.13 3.89 ± 0.04 3.53/7.07 0.12 ± 0.02 ... 7 ... ... 2010EL 139 3.2 23.99 5.23 ± 0.04 3.16/6.32 0.15 ± 0.03 ... 6 ... ... 2010ER 65 SD 21.58 4.69 ± 0.07 ... <0.16 4 ... ... 2010ET 65 SD 30.00 4.96 ± 0.11 3.94/7.88 0.13 ± 0.02 ... 6 ... ... 2010FX 86 SD 26.60 4.34 ± 0.04 7.90/15.80 0.26 ± 0.04 ... 8 ... ... 2010HE 79 3.2 15.04 5.06 ± 0.04 9.75/19.49 0.11 ± 0.02 ... 5 ... ... 2010KZ 39 SD 25.08 4.03 ± 0.01 ... <0.17 3 ... ... 2010PU 75 SD 7.42 5.80 ± 0.07 6.19/12.39 0.27 ± 0.03 ... 4 4.91/9.82 ... 2010RF 43 CN 34.52 3.54 ± 0.04 ... <0.08 7 ... ... 2010RO 64 SD 15.86 4.84 ± 0.02 ... <0.16 3 ... ... 2010TY 53 CN 21.56 5.34 ± 0.03 ... <0.14 4 ... ... 2010VK 201 SD 27.72 4.40 ± 0.07 3.79/7.59 0.30 ± 0.02 ... 8 3.28/6.55 ... 2010VZ 98 SD 3.46 4.81 ± 0.04 ... <0.18 4 4.86/9.72, just below significance criterion ... Notes. a Using the formalism of Elliot et al. (2005): CL = cold classical, CN = Centaurs, SD = scattered disk, M:N = Mean Motion Resonance with Neptune. b The mean heliocentric inclination based on a 10 My integration of the orbit of the object; used for identifying an object as cold classical.

4.2 This Sample

Our dataset includes objects in all dynamical classes (Table 1 provides a numerical summary). We find 15 objects for which we can fit periods to the data (~46% of our sample); eight of these are from the scattered population, one is a Haumea family object, one is classical, and five are resonant objects.

Our sample includes eight objects with amplitudes ≥0.2 mag. Two of the objects with the largest variations are unresolved cold classical binaries and the smallest/faintest objects in our sample (2005 EF298 and 303712 2005 PR3). One of these, 2005 EF298, is best fit with a 4.82 hr single-peaked or 9.65 hr double-peaked period although a period of 6.09/12.18 hr also gives a decent result. We do not have enough data to constrain the period for (303712) 2005 PR3. 2010 VK201, a scattered object, is fit with a period of 3.79 or 7.59 hr and 2007 JF43, a 3:2 resonant object, is fit with a period of 4.76 or 9.52 hr. 2009 YE7, a Haumea family object (Trujillo et al. 2011), is variable at ~0.2 mag, but we were not able to fit a unique period to our dataset. 2010 FX86 is clearly variable (~0.2 mag or greater) within individual nights of observation, though a number of periods are significant above the confidence level including the one we choose at 7.90 hr (single-peaked) or 15.8 hr (double-peaked) for our analyses. (307251) 2002 KW14 was fit with a preferred period of 6.63 hr and an amplitude of 0.25 ± 0.03 mag. The 4.29/8.57 hr and 5.25/10.5 hr period peaks for (307251) 2002 KW14 from Thorin et al. (2012) are still possible; however, only the latter period fits above our confidence level; our light curve amplitudes of 0.25 ± 0.03 and (0.21 or 0.26) ± 0.03 mag, respectively, are in agreement. 2010 PU75 is a scattered object which we fit with a rotation period of 6.19 or 12.39 hr and an amplitude of 0.27 ± 0.03 mag.

We are able to fit periods for another nine of our objects, all with variations <0.18 mag. The best-fit periods range from ~3.2 hr to 19.5 hr, considering both single- and double-peaked light curve interpretations. Three of these objects, 2010 EL139,
2010 EK139 and 2010 ET65, have single-peaked rotation periods <4 hr. 2010 EK139 is the largest object of this set assuming comparable albedos. The double-peaked light curves at 6.32 hr, 7.07 hr, and 7.88 hr, respectively, also give reasonable results. These are good candidates for Jacobi ellipsoids, elongated by their fast spins (Jewitt & Sheppard 2002); they all have light curve amplitudes ~0.13 mag. 2007 J143 and (312645) 2010 EP65 were both fit with preferred single-peaked periods of 6.04 and 7.48 hr, respectively. Both objects are equally well interpreted as double-peaked with periods of 12.08 and 14.97 hr and could also be fit with periods about an hour shorter or longer than the chosen periods. (303775) 2005 QU182 and 2010 HE79 are both fit with single-peaked periods just shy of 10 hr (9.61 and 9.75 hr). Both are likely large enough objects to have their shapes dominated by gravity.

Our preferred period, 6.95/13.89 hr (single/double peaked), for (145452) 2005 RN43 is different than the preferred period of Thirouin et al. (2010). Both of their single-peaked periods: 5.62 and 7.32 hr are nominally consistent with our dataset, but neither period fits our dataset above the confidence level. Our amplitudes are in agreement, 0.04 ± 0.01 and 0.06 ± 0.01 mag, respectively. We fit a period of 4.85 or 9.71 hr to (120178) 2003

Table 4

| Object    | Filter | Julian date | $m_r$ | $\sigma_r$ | $r^c$ | $\Delta^c$ | $\alpha^c$ | L-Time | $H_r$ | $H_r^{\alpha}$ |
|-----------|--------|-------------|-------|------------|-------|------------|------------|--------|------|--------------|
| 2005EF298 | Sloan_r| 2456005.54549| 21.927| 0.027      | 40.655| 39.715     | 0.469      | 330.299| 6.796| 6.892        |
| 2005EF298 | Sloan_r| 2456005.59497| 21.757| 0.021      | 40.655| 39.715     | 0.470      | 330.301| 6.626| 6.722        |
| 2005EF298 | Sloan_r| 2456005.59925| 21.766| 0.021      | 40.655| 39.715     | 0.470      | 330.301| 6.635| 6.731        |
| 2005EF298 | Sloan_r| 2456005.60353| 21.804| 0.022      | 40.655| 39.715     | 0.467      | 330.301| 6.636| 6.731        |
| 2005EF298 | Sloan_r| 2456005.67926| 21.985| 0.026      | 40.655| 39.715     | 0.472      | 330.301| 6.853| 6.950        |
| 2005EF298 | Sloan_r| 2456005.68354| 21.965| 0.024      | 40.655| 39.715     | 0.472      | 330.301| 6.835| 6.935        |
| 2005EF298 | Sloan_r| 2456005.74765| 22.099| 0.028      | 40.655| 39.715     | 0.473      | 330.301| 6.967| 7.064        |
| 2005EF298 | Sloan_r| 2456005.75193| 22.019| 0.027      | 40.655| 39.715     | 0.474      | 330.301| 6.887| 6.984        |

Notes.

a Julian date at the beginning of the exposure, not corrected for light-time.

b Apparent Sloan $r'$ magnitude and corresponding uncertainty on the individual measurement.

c Heliocentric distance, geocentric distance, phase angle, and light time, respectively.

d $H_r^{\alpha}$ is the absolute magnitude calculated using the formalism of Bowell et al. (1989): $H = H_{obs}(\alpha) - \log(r\Delta) + 2.5 \log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$

$G = 0.15 \Phi_1(\alpha) = e^{-3.33 \tan(0.5\alpha)^{0.65}}$ and $\Phi_2(\alpha) = e^{-1.87 \tan(0.5\alpha)^{1.22}}$

e $H_r^{\alpha}(\alpha)$ is the reduced magnitude at unit distance from the Sun and the Earth, uncorrected for phase angle: $H_r^{\alpha}(\alpha) = R_{obs}(\alpha) - 5 \log(r\Delta)$

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
OP$_{32}$, with an amplitude of $0.18 \pm 0.01$ mag, slightly longer then the interpretation of Thirouin et al. (2010); their preferred period of 4.05 hr is not consistent with our dataset, although their light curve amplitude of $0.13 \pm 0.01$ mag is comparable.

One object in our sample is consistent with a long period interpretation, (79360) Sila/Nunam. This object is both a cold classical TNO and a binary currently undergoing mutual occultations and eclipses as reported in Grundy et al. (2012). Our 2011 dataset was included in Grundy et al. (2012). We include in this data sample our 2012 observations. We do not observe enough of the period to fit the data to the mutual orbital period of the components, but our data are consistent with such an interpretation. Our amplitude variation of $<0.17$ mag is also consistent with the $0.14 \pm 0.07$ mag variation reported by Grundy et al. (2012).

### 4.3 Axis Ratio

In addition to rotation period, we can use the amplitude of variation to estimate the sphericity of our objects. Our object sample ranges from $H_V = 2–6.1$ (or $d \sim 1600–250$ km using the formalism of Bowell et al. (1989) and assuming an albedo of 0.1), and includes objects from both the spherical and elongated...
groups. We expect the smaller objects to be elongated, having double-peaked light curves where nominally we can sample the long and short axes of the object twice over a full rotation. If we assume such an object to be triaxial with semi-major axes $a \geq b \geq c$ in rotation about the $c$-axis, the minimum and maximum flux of the rotation curve measured in magnitudes, $\Delta m$, can be used to determine the projection of the body shape (i.e., how spherical the object is) into the plane of the sky:

$$\Delta m = 2.5 \log \frac{a}{b} - 1.25 \log \left( \frac{a^2 \cos^2 \theta + c^2 \sin^2 \theta}{b^2 \cos^2 \theta + c^2 \sin^2 \theta} \right),$$  \hspace{0.5cm} (1)$$

where $\theta$ is the angle at which the rotation axis is inclined to the line of sight (an object with $\theta = 90^\circ$ is being viewed equatorially; Binzel et al. 1989). If we assume that we are in fact viewing the object equatorially, then this equation can be rearranged to give the axis ratio, $a/b = 10^{\Delta m/4.5}$. The axis ratio for our sample ranges from 1.03 to 1.33 with an average of 1.16.

### 4.4 Previous Results

The existing database for the rotation properties of TNOs (including Centaurs) is on the order of 100 objects. About two dozen objects have been studied in extensive detail while many have only been observed in one or two observing campaigns.
Observations generally require substantial amounts of telescope time on 2 m class or larger telescopes for the brightest objects \((m_R \leq 23.0)\), and time on 4 m class or larger telescopes for the fainter population of objects. A variety of studies have been done to estimate typical light curve amplitudes and periods, each study having its own brightness and size limitations. Numerous biases also exist among the datasets: (1) objects with longer periods are harder to observe due to a combination of the fact that objects are up no more than \(\sim 8.5\) hr above 30° (an airmass of 2) at most observing locations if only one telescope facility is used, (2) faint and/or small objects are not possible to observe with 2 m class telescopes, the ones that are easier to get long consecutive stretches of telescope time on, (3) most of the brightest objects are in the Plutino (3:2 resonance) and scattered disk population, so studies of objects by dynamical classification requires access to a combination of telescope sizes and facilities, and (4) observations over a few nights on a single observing run might not result in a unique object period.

The recent summary paper of Duffard et al. (2008) compiles 91 light curves (74 TNOs and 17 Centaurs) from the literature and their own work (inclusive of Thirouin et al. 2010) to conclude that the mean rotation period for all TNOs is 7.35 hr, or 7.71 hr for the TNOs alone, excluding Centaurs. This sample includes objects from all dynamical regions of the Kuiper Belt, as well as a handful of unresolved binary objects. Except for the Centaur population, small sample sizes have limited our ability to investigate correlations between light curves and dynamical properties; however, the number of objects with measurements is now becoming large enough to consider such correlations.

One difficulty of summary analyses for light curves is if an object has been observed, but no unique rotation period has been identified. In some cases, a number of periods are equally plausible in the absence of more data, and all are recorded in the literature. For summary analyses Monte Carlo models can be used to include these results; however, uniquely determined periods are preferable. Another complication is how the light curve is interpreted, as a single- or double-peaked curve. The light curve of an elongated TNO will be due to changes in the projected cross-section of the object as measured at the telescope. The light curve of a spherical TNO, presumed not to have an atmosphere, is most likely to be caused by surface variations in either albedo or topography across the surface of the object. In this case, light curve amplitudes are typically small and, based on asteroid studies, are empirically found to be less than 10%–20% (Magnusson 1991). For TNOs it has been suggested that an amplitude of \(\sim 0.15\) mag is a reasonable break point for interpreting light curve amplitudes as being due primarily to surface albedo variations (\(\leq 0.15\) mag) or due to object elongation \(>0.15\) mag; Sheppard et al. 2008; Thirouin et al. 2010). As the number of good light curves grows and as other methods of shape determination are employed (e.g., occultations; Person et al. 2006), we may be able to better refine this distinction for TNOs as a whole, or for different subsets of the population.

5. DISCUSSION

In the following discussion we include results from this work and that collected from the literature out of the references listed in the caption of Figure 3. We use absolute magnitudes \(H_V\) from the MPC so as to interpret all objects in a consistent manner relative to intrinsic brightness which can be used as a proxy for size. One method of estimating an effective diameter for these objects is to follow the formalism of Bowell et al. (1989), where

\[
\sigma = \frac{10^{(6.259-0.4 \times \log \rho)} - 0.4}{2}
\]

\(d = \frac{10^{(6.259-0.4 \times \log \rho)} - 0.4}{2}\) km and \(\rho\) is albedo. It is known that TNO albedos range from \(\sim 0.04\) to \(\sim 0.8\) (Stansberry et al. 2008). Because the objects in our sample are relatively new discoveries, they do not yet have measured albedos. For our calculations we work in \(H_V\) space, but to give a general reference point on size for Figures 3 and 5 we assume \(\rho = 0.1\). Figure 3 shows a histogram of absolute magnitude for the entire sample of published TNO light curves sub-divided by dynamical classification, with the sample for this work extracted in a separate plot. The majority of objects sampled thus far are from the dynamically scattered population since these objects tend to be intrinsically bright and more easily observed from smaller telescopes.

In Figure 4, we plot the cumulative number of objects with respect to light curve amplitude normalized by the total number of objects in the sample for the entire measured population and also for the sample in this work alone using our fitted amplitudes or upper limits. The solid points/black line shows the results for the full sample, the triangles/red line for the classical objects, the squares/gray line for the resonant objects and the diamonds/blue line for the scattered objects. In both samples the scattered objects typically have smaller amplitude light curves then the larger population. However, scattered objects at all sizes are measured, so size is not the sole explanation for this effect.

In Figure 5 we plot rotation period and amplitude versus absolute magnitude, and find that objects fainter than about \(H_V \sim 5\) appear to have larger amplitude light curves. Using the entire sample, a Spearman rank correlation test (Table 5) between absolute magnitude and light curve amplitude indicates this to be a 3\(\sigma\) result. We also see an indication of correlation between absolute magnitude and single period rotation curves, although this is less than a 3\(\sigma\) result and there is also some ambiguity between single and double peaked light curve interpretations. We consider correlations with orbital properties, but do not find any statistically significant results. If we run the same analysis for only the binaries or Haumea family objects (discussed in Sections 4.4 and 4.5), we also do not find significant correlations. It appears that size has a greater influence over the rotational properties of an object than one particular orbital characteristic, unless there has been obvious interaction with another TNOs as in the case of tidally locked binaries.

Figure 5 also demonstrates that, with the exception of tidally locked objects, the rotation rate for the majority of measured objects is less than 13/26 hr (single-peak/double-peak interpretations), with the mean rotation periods being 6.73 hr and 11.30 hr, respectively (excluding Pluto/Charon and Sila/Nunam). The scatter is relatively small. Modeling by Lacerda (2005) suggests that such a spin distribution is indicative of some level of anisotropic accretion in the early Kuiper Belt.

However, if we compare the rotational properties of objects to each other with respect to dynamical class, binary, or family status (Table 6) we find a 95.60% probability that the classical and scattered object amplitudes come from different distributions and a 94.64% probability that the classical and resonant object amplitudes come from different distributions. If we combine the scattered and resonant objects the significance of the difference increases to 97.05%. We also investigated if our result was significantly affected by the absolute magnitude range of the sample. We could not test for samples brighter than an absolute magnitude of 6.5 because the sample size for the classical objects is too small, however, we plot in Figure 6 the percent results versus absolute magnitude for samples from 6.5 to 12 (the faintest object) in steps of 0.5 mag. The amplitude distinction we find is strongest for all three samples.
et al. (1992), Buie et al. (1997), Tegler et al. (1997), Davies et al. (1998a), Davies et al. (1998b), Luu & Jewitt (1998), Collander-Brown et al. (1999), Romanishin &

Figure 3. Left: histogram of all published TNOs observed for light curves with respect to the absolute magnitude, $H_V$, (taken from the MPC database for consistency), which is used as a proxy for size; the figure on the right highlights the sample from this work. One can estimate effective diameter from this information following the formulation of Bowell et al. (1989) $d = 10^{0.259 - 0.4 H_V - \log \rho}/2$ km and assuming an albedo, $\rho$; we assume $\rho = 0.1$. In addition, objects have been categorized by broad dynamical classification: cold classical TNOs (inclinations < $5^\circ$) are red, scattered TNOs (inclusive of scattered objects, detached objects and Centaurs) are blue, and resonant TNOs are gray. Original references for compiled datapoints in Figures 3–9: Bus et al. (1989), Tholen & Buie (1990), Buie & Bus (1992), Hoffmann et al. (1992), Buie et al. (1997), Tegler et al. (1997), Davies et al. (1998a), Davies et al. (1998b), Lin et al. (2007), Ortiz et al. (2007), Rabinowitz et al. (2007), Sheppard (2007), Dotto et al. (2008), Duffard et al. (2008), Lacerda et al. (2008), Moullet et al. (2008), Rousselot et al. (2008), Thirouin et al. (2012), and this work. See the online journal (Table 9) for specific object details.

(A color version of this figure is available in the online journal.)

| Comparison                     | All Lightcurves | This Work |
|--------------------------------|-----------------|-----------|
|                                 | $N_{obj}$  | $\rho$  | $\text{Sig}^a$ | $N_{obj}$  | $\rho$  | $\text{Sig}^a$ | $N_{obj}$  | $\rho$  | $\text{Sig}^a$ |
| Amplitude, aphelion            | 128      | -0.143 | 0.108 | 24       | -0.309 | 0.141 | ...       | ...       | ...       |
| Amplitude, eccentricity        | 128      | -0.150 | 0.092 | 24       | -0.293 | 0.165 | 9         | 0.092 | 0.814 |
| Amplitude, $H_V$               | 128      | -0.170 | 0.056 | 24       | -0.319 | 0.128 | ...       | ...       | ...       |
| Amplitude, inclination         | 128      | -0.036 | 0.690 | 24       | 0.195  | 0.361 | ...       | ...       | ...       |
| Amplitude, perihelion          | 128      | -0.094 | 0.291 | 24       | -0.038 | 0.860 | ...       | ...       | ...       |
| Single period, aphelion        | 69       | 0.249  | 0.039 | 9        | 0.317  | 0.406 | ...       | ...       | ...       |
| Single period, eccentricity    | 69       | 0.245  | 0.043 | 9        | 0.483  | 0.188 | 5         | -0.900 | 0.037 |
| Single period, $H_V$           | 69       | -0.301 | 0.012 | 9        | -0.267 | 0.488 | 5         | -0.900 | 0.037 |
| Single period, inclination     | 69       | -0.020 | 0.874 | 9        | 0.283  | 0.460 | ...       | ...       | ...       |
| Single period, perihelion      | 69       | 0.013  | 0.916 | 9        | -0.233 | 0.546 | ...       | ...       | ...       |
| Single period, semi-major axis | 69       | 0.191  | 0.116 | 9        | -0.333 | 0.381 | 4         | 0.400  | 0.600 |
| Double period, aphelion        | 67       | 0.171  | 0.165 | 10       | -0.273 | 0.446 | ...       | ...       | ...       |
| Double period, eccentricity    | 67       | 0.057  | 0.646 | 10       | -0.103 | 0.776 | ...       | ...       | ...       |
| Double period, $H_V$           | 67       | -0.143 | 0.249 | 10       | 0.152  | 0.676 | 4         | 0.400  | 0.600 |
| Double period, inclination     | 67       | -0.075 | 0.546 | 10       | -0.515 | 0.128 | ...       | ...       | ...       |
| Double period, perihelion      | 67       | 0.115  | 0.354 | 10       | -0.042 | 0.907 | ...       | ...       | ...       |
| Double period, semi-major axis | 67       | 0.159  | 0.199 | 10       | -0.552 | 0.098 | ...       | ...       | ...       |

Table 5

Spearman’s $\rho$ Rank Correlation

Notes. Pluto/Charon and Sila/Nunam are excluded from the rotation period statistics since their rotations are due to tidal locking.

$^a$ The significance is a value in the interval [0.0, 1.0] where a small value indicates a significant correlation. A 3$\sigma$ result yields a significance of $\sim 0.001$.  

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Figure 4. Cumulative number of TNOs amplitudes (or amplitude limits) normalized to the total number of objects in each dynamical sample: (left) all TNOs and (right) this work only. The black curve is for all TNOs combined, the other samples are as defined such that cold classical objects are red triangles, scattered objects are blue diamonds and resonant objects are gray squares. The number in parenthesis in the legend is the number of objects in the sample for that panel. The scattered population has systematically smaller light curve amplitudes than the classical and resonant populations; this is most evident in the larger sample, although the resonant objects are dominated by the contact binary 2001 QG298. However, scattered objects at all sizes are measured, so size is not the sole explanation for this effect. (A color version of this figure is available in the online journal.)

Table 6

| Sample1                  | Sample2                  | D    | %a  | N1b | N2b |
|--------------------------|--------------------------|------|-----|-----|-----|
| Amplitude non-binary     | Amplitude binary         | 0.21 | 69.03 | 104  | 24  |
| Amplitude classical non-binary | Amplitude classical binary | 0.21 | 4.04  | 13   | 8   |
| Amplitude scattered non-binary | Amplitude scattered binary | 0.31 | 51.78 | 59   | 7   |
| Amplitude resonant non-binary | Amplitude resonant binary | 0.22 | 14.21 | 24   | 9   |
| Amplitude scattered all  | Amplitude Haumea all     | 0.32 | 67.05 | 71   | 9   |
| Amplitude scattered all  | Amplitude resonant all    | 0.08 | 0.23  | 79   | 32  |
| Amplitude classical all  | Amplitude scattered all   | 0.36 | 95.60 | 17   | 79  |
| Amplitude classical all  | Amplitude resonant all    | 0.39 | 94.64 | 17   | 32  |
| Amplitude classical all  | Amplitude scattered & resonant all | 0.36 | 97.05 | 17   | 111 |
| Single period non-binary | Single period binary      | 0.23 | 24.46 | 59   | 9   |
| Double period non-binary | Double period binary      | 0.27 | 48.37 | 58   | 10  |

Notes.

a The level of confidence that the two groups are not drawn from the same parent population.
b The number of objects N1 and N2 used in Sample 1 and Sample 2 respectively.

5.1. Binaries

Binaries are found throughout the Transneptunian belt, though in significantly higher fractions among the cold classical population (29%±7% versus 5.5%±4% for all other classes combined; Noll et al. 2008a, 2008b). A number of formation mechanisms for these systems have been proposed including: (1) physical collisions (Weidenschilling 2002; Canup 2005, 2011), (2) gravitational interactions (Goldreich et al. 2002; Astakhov et al. 2005; Lee et al. 2007; Funato et al. 2004), and (3) gravitational collapse (Nesvorny & Vokrouhlicky 2006). Each of these mechanisms has the potential to influence the rotational properties of these objects, in addition to the tidal and orbital interactions between the binary objects themselves. Tidal interactions can have the effect of synchronizing the rotation period of an object with the mutual binary orbit, as is well known in the case of the (134340) Pluto/Charon system (Tholen & Tedesco 1994). Grundy et al. (2012) and this work also support the interpretation that (79360) S/ila/Nunam is a tidally locked system. There are currently 24 binaries with light curve measurements and/or estimates.
Figure 5. Right: plot of light curve amplitude vs. size (as estimated by $H_V$ magnitude) including objects with only upper limits on their light curve amplitudes. The colors and symbols are the same as in Figure 4; solid circles identify the results of this work while open points show results from the literature. A dashed line is drawn at an amplitude of 0.15 mag which is a possible break for interpreting light curve amplitudes as being due primarily to surface albedo variations ($\leq 0.15$ mag) or due to object elongation ($> 0.15$ mag; Sheppard et al. 2008; Thirouin et al. 2010). Left: plot of rotation period (single and double-peaked interpretations) vs. size (as estimated by $H_V$ magnitude) for all objects with published periods. Open symbols indicate single-peaked rotation period interpretation while solid symbols indicate double-peaked period interpretation; some objects do not have unique interpretations so both results are plotted. This work’s results are plotted with circles. The area below a rotation period of 3.3 hr is grayed out since faster rotation rates would result in the objects being gravitationally unstable assuming a composition of pure ice (Romanishin & Tegler 1999).

(A color version of this figure is available in the online journal.)

Our sample includes five binary objects and, as mentioned in Section 4.1, two of these objects have the largest variations and are the smallest objects in our sample. The two binaries that do not show significant variation are the brightest of our binary sample, consistent with the idea that smaller objects have larger amplitude light curves. In Figure 7 we plot the light curve characteristics of all the binaries in the literature (references can be found in the figure caption). In a statistical sense, the sample is still small, however we note that the same low amplitude characteristic of the scattered objects is seen. The cold classical objects have the largest amplitudes with the exception of the resonant object 2001 QG298, whose large amplitude light curve is consistent with a contact binary interpretation (Sheppard & Jewitt 2004; Takahashi & Ip 2004). We find hints that the binary amplitudes as a whole may be slightly larger then the non-binary population, but overall the distributions are similar and we are hesitant to over-interpret the statistics.

5.2. Haumea Family Objects

In the asteroid belt, much has been learned through study of asteroid families with respect to both dynamical and photometric properties. Modeling the dynamics of collision family members in many cases can trace back a timeframe for when family creation occurred (Nesvorny & Vokrouhlicky 2006). In the
Koronis family, spin studies of large numbers of objects of various sizes (Slivan 2002; Slivan et al. 2008, 2009) have demonstrated markedly nonrandom alignments of spin obliquities and correlations with spin rates which in the asteroid belt are interpreted to be thermally driven (Vokrouhlický et al. 2003). The modification of these spin rates is the result of the Yarkovsky (YORP) effect which disproportionately heats non-spherical objects and has the effect of increasing rotation rates of objects; this effect is stronger the smaller the object. YORP is not effective in the Kuiper Belt since objects are too distant from the Sun.

In the Kuiper Belt one dynamical family has been identified through spectroscopic studies (Barkume et al. 2006), and confirmed with dynamical integrations (Ragozzine & Brown 2007). Rotational studies of the largest body, (136108) Haumea, found it to have a rapid rotation, 3.9154 ± 0.0002 hr (double-peaked) with an amplitude of 0.28 ± 0.04 mag, which can be explained as the result of a physical collision (Rabinowitz et al. 2006; Schlichting & Sari 2009; Leinhardt et al. 2010; Lykawka et al. 2012), although Ortiz et al. (2012) argue that such a system could also be created through rotational fission due to collisional spin-up. Studies of the rotation properties of the Haumea family may provide insight for spin properties resultant from a formation mechanism independent from modification by thermal factors. It is possible that small collisions play a roll in rotational modification, but to date this has not been demonstrated. It is believed that large collisions influence the spin properties of the target and the material ejected during such an event (Paolicchi et al. 2002). If the Haumea system is the result of a collision, one might expect the spin properties of resultant family members to be different as a group from the background TNO light curve distribution. Perhaps these objects are more elongated as a result of the collision, or spinning more rapidly (small objects) or more slowly (large objects), depending on the energy of the initial collision.

The numbers are still too small for statistics and many of the smaller objects still need to be studied; however, we present in Figure 8 the current light curve characteristics of nine objects from this work and the literature. All have rotation periods (where measured) \( \leq 10 \) hr and distinguishable light curve amplitudes. The mean single-peaked period is 5.60 hr and the mean double-peaked period is 7.39 hr inclusive of

Figure 6. Summary results of K-S test of absolute magnitude limits vs. light curve properties in bins of 0.5 mag for each of the samples in Table 5. The amplitude distinction that we find is strongest for all three samples (classical/resonant, classical/scattered, and classical/scattered + resonant) with an absolute magnitude limit brighter than 7.0; however, it is strong in all magnitude bins and we believe that the effect is real, not size dependent.
6. PHASE CURVE AND COLOR RESULTS

A phase curve describes the brightness of a TNO as a function of its phase angle, the angle made between the Sun, the TNO, and the observer (Earth); for TNOs, the maximum angle is \( \sim 2^\circ \). It is linear outside of a few tenths of a degree, but studies of asteroids and moons of the giant planets find nonlinear brightening as the phase gets close to zero (Verbiscer et al. 2005). The surge can be explained by two physical mechanisms, shadow hiding and coherent backscattering: both are related to what is happening at the surface of the TNO. Shadow hiding is the result of hills, boulders, or a mix of light and dark ices on the surface of the object. At low phase angles, no shadows occur and the object appears brighter than at larger phase angles where shadows contribute to the disk-integrated photometry. Coherent backscattering occurs when multiply scattered rays bounce off the surface of the object and follow the same path back to the observer; the light rays add together and a brightening occurs. Near-zero-phase angle light paths interfere more constructively as seen by the observer than at larger phase angles (Schaefer et al. 2009).

Slightly less than one-third of our objects span a large enough region of phase angle space (\( \geq 0.3^\circ \)) for us to estimate the linear phase coefficient, which can be expressed in flux as \( \phi(\alpha) = 10^{-0.4\beta_\alpha} \), where \( \beta \) is the phase coefficient in magnitudes per degree at phase angles, \( \alpha < 2^\circ \). Figure 9 plots our measurements and Table 7 gives the results of our fit for each object. We find an average phase coefficient of \( \beta_R = 0.23 \text{ mag deg}^{-1} \) for the objects we can measure (with \( \alpha > 0.2^\circ \), higher than that found by Belskaya et al. (2003), although consistent with some of the individual values listed in Rabinowitz et al. (2007) and Schaefer et al. (2009).
Figure 8. Inventory of light curve properties for 9 Haumea family objects. The solid line in the upper right plot is the cumulative curve from Figure 5 for comparison. In the lower left plot solid circles are single-peaked period interpretations and open circles are double-peak period interpretations. All objects have rotation periods (where measured) \( \leq 10 \) hr and distinguishable light curve amplitudes. At this point, only the brightest Haumea family objects have been observed. Since most of the amplitudes are small, it is likely that they can be interpreted as spherical objects with surface variations due to albedo features. References: Sheppard & Jewitt (2002), Sheppard & Jewitt (2003), Lacerda et al. (2008), Thirouin et al. (2012), and this work.

A (color version of this figure is available in the online journal.)

| Object | Phase Angle Minimum (°) | Phase Angle Maximum (°) | Phase Angle Range (°) | \( \beta \) (mag deg\(^{-1}\)) | \( H_\beta \) (1,1,0) |
|--------|------------------------|------------------------|----------------------|-----------------|-----------------|
| 119951 | 1.17                   | 1.46                   | 0.30                 | 0.13 ± 0.06     | 4.48 ± 0.08     |
| 305543 | 0.60                   | 0.99                   | 0.39                 | 0.23 ± 0.14     | 4.28 ± 0.12     |
| 2010FX\(_{56}\) | 0.60 | 0.99 | 0.39 | 0.23 ± 0.14 | 4.28 ± 0.12 |
| 2010EK\(_{139}\) | 0.63 | 1.04 | 0.41 | 0.19 ± 0.06 | 3.87 ± 0.05 |
| 2010EL\(_{139}\) | 0.54 | 0.97 | 0.44 | 0.05 ± 0.07 | 5.30 ± 0.06 |
| 120178 | 0.43                   | 0.87                   | 0.44                 | 0.13 ± 0.11     | 3.85 ± 0.08     |
| *2007JF\(_{43}\) | 0.19 | 1.05 | 0.86 | 0.20 ± 0.05 | 5.22 ± 0.04 |
| *2010ET\(_{65}\) | 0.13 | 1.21 | 1.08 | 0.34 ± 0.02 | 4.87 ± 0.01 |
| *278361 | 0.22 | 1.32 | 1.09 | 0.56 ± 0.03 | 3.68 ± 0.03 |
| *312645 | 0.16 | 1.28 | 1.12 | 0.11 ± 0.03 | 5.34 ± 0.02 |
| *2007JH\(_{43}\) | 0.14 | 1.28 | 1.13 | 0.20 ± 0.01 | 4.45 ± 0.01 |

Note. * Since \( \alpha < 0.2 \), these phase curves could be influenced by opposition surge effects.

2007 JJ\(_{43}\), which has the steepest slope and relatively small uncertainty, is measured near a phase angle of 0°2, close to the region where the opposition surge can have an effect. We do not have any measurements between the two extremes so we suggest these values be used with caution. We do not have albedo and color-phase measurements for these objects, but based on the criteria established in Schaefer et al. (2009) for the phase curve slope, we infer that if we are seeing a surge effect it is most likely due to the coherent backscattering mechanism.

Additionally, we collected color information on one night for each object. The individual measurements can be found in Table 8 and the cumulative results are plotted in Figure 10. Our objects span the range of TNO colors and are redder than the Sun with the exception of 2009 YE\(_{7}\), which is known to be a Haumea family member (Trujillo et al. 2011). None of the other
was observed at a phase angle (Schaefer et al. 2009). However, (278361) 2007 JJ43 has a steep slope and relatively small scatter. It may be that this object displays strong opposition effects since it was observed at a phase angle $< 0.2$.

**Figure 9.** Phase curves for objects in our sample with phase observations $\geq 0.3$. Most of our objects have phase values similar to those found in other TNO studies (Schaefer et al. 2009). However, (278361) 2007 JJ43 has a steep slope and relatively small scatter. It may be that this object displays strong opposition effects since it was observed at a phase angle $< 0.2$.

| Object  | Midtime JD | $r'$  | $g'$  | $i'$  | $g'-r'$ | $r'-i'$ |
|---------|------------|------|------|------|--------|--------|
| 2006HJ123 | 2455654.68228 | 21.68 ± 0.03 | 22.50 ± 0.08 | 21.09 ± 0.02 | 0.82 ± 0.08 | 1.41 ± 0.08 | 0.59 ± 0.03 |
| 2007FF13 | 2455653.87518 | 21.23 ± 0.03 | 22.11 ± 0.02 | 20.73 ± 0.01 | 0.96 ± 0.03 | 1.46 ± 0.02 | 0.50 ± 0.03 |
| 2007JJ43 | 2455606.71009 | 20.49 ± 0.03 | 21.17 ± 0.03 | 20.08 ± 0.01 | 0.68 ± 0.04 | 1.09 ± 0.03 | 0.41 ± 0.03 |
| 2007JH45 | 2455633.79553 | 20.98 ± 0.03 | 21.55 ± 0.08 | 20.58 ± 0.03 | 0.99 ± 0.04 | 0.39 ± 0.04 |
| 2008QY40 | 2455836.61329 | 20.96 ± 0.02 | 21.71 ± 0.02 | 21.13 ± 0.03 | 0.31 ± 0.03 | 0.59 ± 0.03 | 0.28 ± 0.04 |
| 2009YE1 | 2455835.80300 | 21.41 ± 0.03 | 21.71 ± 0.02 | 21.13 ± 0.03 | 0.31 ± 0.03 | 0.59 ± 0.03 | 0.28 ± 0.04 |
| 2010FX86 | 2455867.71400 | 21.32 ± 0.12 | 21.81 ± 0.05 | 21.10 ± 0.06 | 0.49 ± 0.13 | 0.71 ± 0.08 | 0.22 ± 0.13 |
| 2010JF43 | 2455935.79418 | 19.88 ± 0.02 | 20.68 ± 0.01 | 19.55 ± 0.01 | 0.80 ± 0.02 | 1.13 ± 0.01 | 0.33 ± 0.02 |
| 2010JH43 | 2455929.73057 | 21.02 ± 0.04 | 21.77 ± 0.11 | 20.60 ± 0.03 | 0.75 ± 0.11 | 1.17 ± 0.11 | 0.42 ± 0.05 |
| 2010JX50 | 2456322.77304 | 20.56 ± 0.03 | 21.42 ± 0.05 | 19.97 ± 0.02 | 0.86 ± 0.06 | 1.45 ± 0.05 | 0.59 ± 0.03 |
| 2010JK51 | 2456731.50908 | 20.52 ± 0.09 | 21.25 ± 0.08 | 20.14 ± 0.08 | 0.73 ± 0.12 | 1.12 ± 0.11 | 0.38 ± 0.12 |
| 2010ET65 | 245629.68126 | 20.94 ± 0.02 | 21.42 ± 0.03 | 20.28 ± 0.03 | 0.48 ± 0.04 | 1.14 ± 0.04 | 0.66 ± 0.03 |
| 2010FX66 | 2456566.60667 | 20.99 ± 0.02 | 21.82 ± 0.04 | 20.68 ± 0.03 | 0.83 ± 0.05 | 1.14 ± 0.05 | 0.32 ± 0.03 |
| 2010HE19 | 2455635.77667 | 20.70 ± 0.01 | 21.54 ± 0.02 | 20.36 ± 0.01 | 0.84 ± 0.02 | 1.18 ± 0.02 | 0.34 ± 0.01 |
| 2010FE13 | 2455833.55508 | 20.78 ± 0.01 | 21.58 ± 0.03 | 20.38 ± 0.02 | 0.80 ± 0.03 | 1.21 ± 0.04 | 0.41 ± 0.03 |
| 2010TY31 | 2455855.75690 | 20.65 ± 0.02 | 21.24 ± 0.01 | 20.48 ± 0.02 | 0.60 ± 0.02 | 0.77 ± 0.02 | 0.17 ± 0.03 |
| 2010VZ98 | 2455855.80814 | 20.55 ± 0.01 | 21.39 ± 0.03 | 20.02 ± 0.01 | 0.85 ± 0.04 | 1.37 ± 0.04 | 0.53 ± 0.02 |
Table 9
Light Curve Compilation

| Num  | Name   | Desig  | Class            | (i) | ssign | Single Peak | Double Peak | Asign | Amplitude | Absolute | Semi | ecc  | inc | perihelion | aphelion | Ref       |
|------|--------|--------|------------------|-----|-------|-------------|-------------|-------|------------|----------|------|------|-----|------------|----------|-----------|
| 225088 | X 2007OR10 | 10:3:E | 34.72 eq 0 0 eq 0 0 eq | 0.09 | 0.02 | 2 n N 67.037 0.501 30.765 33.451 100.623 | This work |
| 119979 | X 2002WC19  | 2:1E | 7.6 eq 0 0 eq 0 0 it | 0.03 | 0 5.1 y N 48.14 0.263 9.177 35.479 60.801 | S07      |
| 312645 | X 2010EP65   | 2:1E | 19.32 eq 7.48 0 eq 14.97 0 eq | 0.17 | 0.02 | 5.6 n N 47.426 0.303 18.922 33.056 61.796 | This work |
| 26308  | X 1998SM165  | 2:1E + 6:3EI 13.07 eq 3.983 0 eq 7.1 0.1 eq | 0.56 | 0.03 | 5.8 y N 48.004 0.373 13.477 30.099 65.909 | SJ02     |

Notes. Column detailed definitions: (1) MPC number; X = not numbered. (2) MPC name; X = not named. (3) MPC preliminary designation. (4) Dynamical classification. (5) Mean inclination over 10 My integration. (6) Sign for single peak period value. (7) Single peak interpretation. (8) Uncertainty in single peak value. (9) Sign for double peak period value. (10) Double peak interpretation. (11) Uncertainty in double peak value. (12) Sign for amplitude value. (13) Amplitude of light curve or variation. (14) Uncertainty in amplitude. (15) Absolute MPC Jₐ magnitude. (16) Known binary; yes or no. (17) Identified Haumea family object; yes or no. (18) Semi-major axis of heliocentric orbit. (19) Eccentricity of heliocentric orbit. (20) Inclination of heliocentric orbit. (21) Perihelion of heliocentric orbit. (22) Aphelion of heliocentric orbit. (23) Shortened reference or combination of references; last name initial of author (or combination of initials) and year.

Note: A value of “0” has been used if the information is unknown as a way to easily exclude or extract values while selecting samples.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
objects for which we measured colors are extreme compared to other objects in the Kuiper Belt (Sheppard 2010; Benecchi et al. 2011; Fraser et al. 2012).

7. CONCLUSIONS

We have presented light curve results for 32 large Southern Hemisphere TNOs. We can fit rotation periods with statistically significant results for 15 of these and place amplitude limits on the light curves of 17 other objects. All of the objects in our sample have amplitudes $\lesssim$0.3 mag with periods $\lesssim$10 hr (assuming a single-peaked interpretation) with the exception of (79360) Sila/Nunam for which our data are consistent with the mutual orbit binary period. We find an average axis ratio of 1.16 suggestive of albedo variations on these objects. Combining light curve results from the literature with our measurements we find a correlation between light curve amplitude and absolute magnitude at the 3σ level, with small objects having larger amplitudes. However, the correlation is not as statistically significant if one considers the binary or Haumea family populations on their own. We suggest that size has a greater influence over the rotational properties of an object than one particular orbital component. We also find that comparison of light curve amplitude with respect to dynamical population results in statistically different distributions between the classical/scattered and classical/resonant populations at the 95.60% and 94.64% levels, respectively, with the classical objects having higher amplitude light curves. This statistic is 97.05% if the scattered and resonant parameters are combined. Perhaps multiple factors are at work, objects in more stirred-up regions (characteristics of binaries demonstrate that the cold classical region has been significantly less perturbed than the scattered and resonant populations in particular with respect to the number of binary systems and their orbital properties; Grundy et al. 2010; Parker et al. 2011) have experienced greater interaction with other bodies and have likewise had their shapes more greatly altered. Large bodies are less susceptible to large scale changes unless collisions are of comparably sized objects. The properties of binary light curves are largely consistent with the greater TNO population except in the case of tidally locked systems. The nine Haumea family objects with measured light curves have rotation periods $<$10 hr; none have completely flat light curves. It is likely that all of these objects are large enough to be dominated by surface albedo variations; alternatively, if all Haumea family objects have high albedos, then the objects are actually smaller and the light curve properties would be dominated by shape.

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