ANALYSIS OF THE ROTATIONAL PROPERTIES OF KUIPER BELT OBJECTS

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ABSTRACT

We use optical data on 10 Kuiper Belt objects (KBOs) to investigate their rotational properties. Of the 10, 3 (30\%) exhibit light variations with amplitude $\Delta m \geq 0.15$ mag, and 1 out of 10 (10\%) has $\Delta m \geq 0.40$ mag, which is in good agreement with previous surveys. These data, in combination with the existing database, are used to discuss the rotational periods, shapes, and densities of KBOs. We find that, in the sampled size range, KBOs have a higher fraction of low-amplitude light curves and rotate slower than main-belt asteroids. The data also show that the rotational properties and the shapes of KBOs depend on size. If we split the database of KBO rotational properties into two size ranges with diameters larger and smaller than 400 km, we find that (1) the mean light-curve amplitudes of the two groups are different with 98.5\% confidence, (2) the corresponding power-law shape distributions seem to be different, although the existing data are too sparse to render this difference significant, and (3) the two groups occupy different regions on a spin period–versus–light-curve amplitude diagram. These differences are interpreted in the context of KBO collisional evolution.

Key words: Kuiper Belt — minor planets, asteroids — solar system: general

1. INTRODUCTION

The Kuiper Belt (KB) is an assembly of mostly small icy objects, orbiting the Sun beyond Neptune. Kuiper Belt objects (KBOs) are likely remnants of outer solar system planetesimals (Jewitt & Luu 1993). Their physical, chemical, and dynamical properties should therefore provide valuable information regarding both the environment and the physical processes responsible for planet formation.

At the time of writing, roughly 1000 KBOs are known, half of which have been followed for more than one opposition. A total of $\approx 10^5$ objects larger than 50 km are thought to orbit the Sun beyond Neptune (Jewitt & Luu 2000). Studies of KB orbits have revealed an intricate dynamical structure, with signatures of interactions with Neptune (Malhotra 1995). The size distribution follows a differential power law of index $q = 4$ for bodies $\geq 50$ km (Trujillo et al. 2001a), becoming slightly shallower at smaller sizes (Bernstein et al. 2004).

KBO colors show a large diversity, from slightly blue to very red (Luu & Jewitt 1996; Trujillo & Romanishin 2000; Jewitt & Luu 2001), and seem to correlate with inclination and/or perihelion distance (e.g., Jewitt & Luu 2001; Doressoundiram et al. 2002; Trujillo & Brown 2002). The few low-resolution optical and near-IR KBO spectra are mostly featureless, with the exception of a weak 2 $\mu$m water ice absorption line present in some of them (Brown et al. 1999; Jewitt & Luu 2001) and strong methane absorption on 2003 UB\textsubscript{113} (Brown et al. 2005).

About 4\% of known KBOs are binaries with separations larger than 0\'15 (Noll et al. 2002). All the observed binaries have primary-to-secondary mass ratios $\approx 1$. Two binary creation models have been proposed. Weidenschilling (2002) favors the idea that binaries form in three-body encounters. This model requires a 100 times more dense Kuiper Belt at the epoch of binary formation and predicts a higher abundance of large-separation binaries. An alternative scenario (Goldreich et al. 2002), in which the energy needed to bind the orbits of two approaching bodies is drawn from the surrounding swarm of smaller objects, also requires a much higher density of KBOs than the present, but it predicts a larger fraction of close binaries. Recently, Sheppard & Jewitt (2004) have shown evidence that 2001 QG\textsubscript{298} could be a close or contact binary KBO and estimated the fraction of similar objects in the Belt to be $\approx 10\%$–$20\%$.

Other physical properties of KBOs, such as their shapes, densities, and albedos, are still poorly constrained. This is mainly because KBOs are extremely faint, with mean apparent red magnitude $m_R \sim 23$ (Trujillo et al. 2001b).

The study of KBO rotational properties through time-series broadband optical photometry has proved to be the most successful technique to date for investigating some of these physical properties. Light variations of KBOs are believed to be caused mainly by their aspherical shape; as KBOs rotate in space, their projected cross sections change, resulting in periodic brightness variations.

One of the best examples to date of a KBO light curve—and what can be learned from it—is that of (20000) Varuna (Jewitt & Sheppard 2002). The authors explained the light curve of (20000) Varuna as a consequence of its elongated shape (axis ratio, $a/b \sim 1.5$). They further argued that the object is centripetally deformed by rotation because of its low-density “rubble pile” structure. The term “rubble pile” is generally used to refer to gravitationally bound aggregates of smaller fragments. The existence of rubble piles is thought to be due to continuing mutual collisions throughout the age of the solar system, which gradually fracture the interiors of objects. Rotating rubble piles can adjust their shapes

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to balance centripetal acceleration and self-gravity. The resulting equilibrium shapes have been studied in the extreme case of fluid bodies and depend on the body’s density and spin rate (Chandrasekhar 1969).

Lacerda & Lu (2003, hereafter LL03a) showed that under reasonable assumptions the fraction of KBOs with detectable light curves can be used to constrain the shape distribution of these objects. A follow-up (Luu & Lacerda 2003, hereafter LL03b) on this work, using a database of light-curve properties of 33 KBOs (Sheppard & Jewitt 2002 [hereafter SJ02], 2003), showed that although most Kuiper Belt objects (~85%) have shapes that are close to spherical ($a/b \leq 1.5$), there is a significant fraction (~12%) with highly aspherical shapes ($a/b \geq 1.7$).

In this paper we use optical data on 10 KBOs to investigate the amplitudes and periods of their light curves. These data are used in combination with the existing database to investigate the distributions of KBO spin periods and shapes. We discuss their implications for the inner structure and collisional evolution of objects in the Kuiper Belt.

2. OBSERVATIONS AND PHOTOMETRY

We collected time-series optical data on 10 KBOs at the Isaac Newton 2.5 m (INT) and William Herschel 4 m (WHT) telescopes. The INT Wide Field Camera (WFC) is a mosaic of four E2V 2048 × 4096 CCDs, each with a pixel scale of 0.′′24 pixel−1 and spanning approximately 11.′3 × 22.′5 in the plane of the sky. The targets are imaged through a Johnson R filter. The WHT prime focus camera consists of two E2V 4096 × 4096 CCDs with a pixel scale of 0.′′24 pixel−1 and covers a sky-projected area of 2 × 8′/2 × 16′.4. With this camera we used a Harris R filter. The seeing for the whole set of observations ranged from 0.′′85 to 1′′9 FWHM. We tracked both telescopes at sidereal rate and kept integration times used for each object sufficiently short to avoid errors in the photometry due to trailing effects (see Table 1). No light-travel time corrections have been made.

We reduced the data using standard techniques. The sky background in the flat-fielded images shows variations of less than 1% across the chip. Background variations between consecutive nights were less than 5% for most of the data. Cosmic rays were removed with the package LA-Cosmic (van Dokkum 2001).

We performed aperture photometry on all objects in the field using the SExtractor software package (Bertin & Arnouts 1996). This software performs circular aperture measurements on each object in a frame and puts out a catalog of both the magnitudes and the associated errors. Below we describe how we obtained a best estimate of the errors. We used apertures ranging from 1.5 to 2.0 times the FWHM for each frame and selected the aperture that maximized the ratio of signal-to-noise. An extra aperture of five FWHMs was used to look for possible seeing-dependent trends in our photometry. The catalogs were matched by selecting only the sources that are present in all frames. The slow movement of KBOs from night to night allows us to successfully match a large number of sources in consecutive nights. We discarded all saturated sources, as well as those identified to be galaxies.

| Object       | Obs. Date | Telescope | Seeing | Mvt. Rate | Int. Time | R.A. | Decl. | $R_e$ | $\Delta l$ | $\alpha$ |
|--------------|-----------|-----------|--------|-----------|-----------|------|-------|------|----------|---------|
| (19308) 1996 TO66 | 1999 Oct 1 | WHT | 1.5 | 2.89 | 500 | 23.5946 | -03.3642 | 45.950 | 44.958 | 0.1594 |
| (1996 TS6) | 1999 Sep 30 | WHT | 1.3 | 2.62 | 400, 600 | 02.2606 | -21.403 | 38.778 | 37.957 | 0.8619 |
| (1996 TS6) | 1999 Oct 1 | WHT | 1.1 | 2.67 | 600 | 02.2602 | -21.4050 | 38.778 | 37.948 | 0.8436 |
| (1996 TS6) | 1999 Oct 2 | WHT | 1.5 | 2.70 | 600, 900 | 02.2558 | -21.4035 | 38.778 | 37.939 | 0.8225 |
| (35671) 1998 SN6 | 1999 Sep 29 | INT | 1.5 | 3.24 | 360, 400 | 23.3246 | -01.1815 | 38.202 | 37.226 | 0.3341 |
| (35671) 1998 SN6 | 1999 Sep 30 | INT | 1.4 | 3.22 | 360 | 23.3241 | -01.1847 | 38.202 | 37.230 | 0.3594 |
| (19521) Chaos | 1999 Oct 1 | INT | 1.0 | 1.75 | 360, 400, 600 | 03.4437 | +21.3058 | 42.399 | 41.766 | 0.1061 |
| (19521) Chaos | 1999 Oct 2 | INT | 1.5 | 1.79 | 400, 600 | 03.4434 | +21.3054 | 42.399 | 41.755 | 0.1084 |
| (35671) 1998 SN6 | 1999 Sep 1 | WHT | 1.5 | 3.24 | 360 | 02.2602 | -21.4050 | 38.778 | 37.939 | 0.8225 |
| (35671) 1998 SN6 | 1999 Sep 30 | INT | 1.4 | 3.22 | 360 | 23.3241 | -01.1847 | 38.202 | 37.230 | 0.3594 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a UT date of observation.
b Average seeing of the data.
c Average rate of motion of KBO.
d Integration times used.
e KBO-Sun distance.
f KBO-Earth distance.
g Phase angle (Sun-object-Earth angle) of observation.

TABLE 1
OBSERVING CONDITIONS AND GEOMETRY
The KBO light curves were obtained from differential photometry with respect to the brightest nonvariable field stars. An average of the magnitudes of the brightest stars (the reference stars) provides a reference for differential photometry in each frame. This method allows for small-amplitude brightness variations to be detected even under nonphotometric conditions.

The uncertainty in the relative photometry was calculated from the scatter in the photometry of field stars that are similar to the KBOs in brightness (the comparison stars; see Fig. 1).

TABLE 2

| Object | Class | H | i | e | a |
|--------|-------|---|---|---|---|
| (19308) 1996 TO66........... | C | 4.5 | 27.50 | 0.12 | 43.20 |
| 1996 TS66................... | C | 6.4 | 7.30 | 0.13 | 44.00 |
| (35671) 1998 SN165......... | C | 5.1 | 4.60 | 0.05 | 37.80 |
| (19521) Chaos................ | C | 4.9 | 12.00 | 0.11 | 45.90 |
| (79983) 1999 DF3............ | C | 6.1 | 9.80 | 0.15 | 46.80 |
| (66652) 1999 RZ253.......... | C | 6.2 | 3.80 | 0.07 | 42.50 |
| (47171) 1999 TC6............ | P | 4.9 | 8.40 | 0.22 | 39.30 |
| (38628) Huya................ | P | 4.7 | 15.50 | 0.28 | 39.50 |
| 2001 CZ31................... | C | 5.4 | 10.20 | 0.12 | 45.60 |

a Dynamical class (C = Classical KBO, P = Plutino, b = binary KBO).
b Absolute magnitude.
c Orbital inclination.
d Orbital eccentricity.
e Semimajor axis.

This error estimate is more robust than the errors provided by SExtractor (see below), and was used to verify the accuracy of the latter. This procedure resulted in consistent time series brightness data for ~100 objects (KBOs and field stars) in a time span of two to three consecutive nights.

We observed Landolt standard stars whenever conditions were photometric, and used them to calibrate the zero point of the magnitude scale. The extinction coefficient was obtained from the reference stars.

Since not all nights were photometric the light curves are presented as variations with respect to the mean brightness. These yield the correct amplitudes and periods of the light curves but do not provide their absolute magnitudes.

The orbital parameters and other properties of the observed KBOs are given in Table 2. Tables 3, 4, 5, and 6 list the absolute R-magnitude photometric measurements obtained for (19308) 1996 TO66, 1996 TS66, (35671) 1998 SN165, and (19521) Chaos, respectively. Tables 7 and 8 list the mean-subtracted R-band data for (79983) 1999 DF3 and 2001 CZ31.

3. LIGHT-CURVE ANALYSIS

The results in this paper depend solely on the amplitude and period of the KBO light curves. It is therefore important to accurately determine these parameters and the associated uncertainties.

3.1. Can We Detect the KBO Brightness Variation?

We begin by investigating whether the observed brightness variations are intrinsic to the KBO, i.e., if the KBO’s intrinsic brightness variations are detectable given our uncertainties. This was done by comparing the frame-to-frame scatter in the KBO optical data with that of (~10–20) comparison stars.

To visually compare the scatter in the magnitudes of the reference stars (see § 2), comparison stars, and KBOs, we plot a histogram of their frame-to-frame variances (see Fig. 2). In general such a histogram should show the reference stars clustered at the lowest variances, followed by the comparison stars spread over larger variances. If the KBO appears isolated at much higher variances than both groups of stars (e.g., Fig. 2f), then its brightness modulations are significant. Conversely, if the KBO is clustered with the stars (e.g., Fig. 2f), any periodic brightness variations would be below the detection threshold.

Figure 1 shows the dependence of the uncertainties on magnitude. Objects that do not fall on the rising curve traced out by
the stars must have intrinsic brightness variations. By calculating the mean and spread of the variance for the comparison stars (crosses) we can calculate our photometric uncertainties and thus determine whether the KBO brightness variations are significant ($\geq 3 \sigma$).

### 3.2. Period Determination

In the cases in which significant brightness variations (see § 3.1) were detected in the light curves, the phase dispersion minimization method was used (PDM; Stellingwerf 1978) to look for periodicities in the data. For each test period, PDM computes a zonation method was used (PDM; Stellingwerf 1978) to look for periodicities in the data. For each test period, PDM computes a zonation method was used (PDM; Stellingwerf 1978) to look for periodicities in the data.

We ran PDM on each generated data set to obtain a distribution of best-fit periods.

### 3.3. Amplitude Determination

We used a Monte Carlo experiment to determine the amplitude of the light curves for which a period was found. We generated several artificial data sets by randomizing each point within the error bar. Each artificial data set was fitted with a Fourier series, using the best-fit period, and the mode and central 68% of...
the distribution of amplitudes were taken as the light-curve amplitude and 1 \( \sigma \) uncertainty, respectively. For the null light curves, i.e., those in which no significant variation was detected, we subtracted the typical error bar size from the total amplitude of the data to obtain an upper limit to the amplitude of the KBO photometric variation.

4. RESULTS

In this section we present the results of the light-curve analysis for each of the observed KBOs. We found significant brightness variations (\( \Delta m > 0.15 \) mag) for 3 out of 10 KBOs (30%), and \( \Delta m \geq 0.40 \) mag for 1 out of 10 (10%). This is consistent with previously published results: SJ02 found a fraction of 31% with \( \Delta m > 0.15 \) mag and 23% with \( \Delta m \geq 0.40 \) mag, both consistent with our results. The other seven KBOs do not show detectable variations. The results are summarized in Table 9.

4.1. 1998 SN<sub>165</sub>

The brightness of (35671) 1998 SN<sub>165</sub> varies significantly (>5 \( \sigma \)) more than that of the comparison stars (see Figs. 1 and 2c). The periodogram for this KBO shows a very broad minimum around \( P = 9 \) hr (Fig. 3a). The degeneracy implied by the broad minimum would only be resolved with additional data. A slight weaker minimum is seen at \( P = 6.5 \) hr, which is close to a 24 hr alias of \( P = 9 \) hr.

Peixinho et al. (2002, hereafter PDR02) observed this object in 2000 September, but having only one night’s worth of data, they did not succeed in determining this object’s rotational period unambiguously. We used their data to solve the degeneracy in our PDM result. The PDR02 data have not been absolutely calibrated, and the magnitudes are given relative to a bright field star. To be able to combine it with our own data we had to subtract the mean magnitudes. Our periodogram of (35671) 1998 SN<sub>165</sub> (centered on the broad minimum) is shown in Figure 3 and can be compared with the revised periodogram obtained with our data combined with the PDR02 data (Fig. 3c). The minima become much clearer with the additional data, but because of the 1 yr time difference between the two observational campaigns, many close aliases appear in the periodogram. The absolute minimum, at \( P = 8.84 \) hr, corresponds to a double-peaked light curve (see Fig. 4). The second-best fit, \( P = 8.7 \) hr, produces a more scattered phase plot, in which the peak in the PDR02 data coincides with our night 2. Period \( P = 8.84 \) hr was also favored by the Monte Carlo method described in § 3.2, being identified as the best fit in 55% of the cases versus 35% for \( P = 8.7 \) hr. The large size of the error bars compared to the amplitude is responsible for the ambiguity in the result. We use \( P = 8.84 \) hr in the rest of the paper because it was consistently selected as the best fit.
1999 DF9 is shown in Figure 5. The best-fit period is described in § 3.3, with $\Delta m = 0.16 \pm 0.01$ mag. This value was calculated using only our data, but it did not change when recalculated adding the PDR02 data.

4.2. 1999 DF9

KBO (79983) 1999 DF9 shows large-amplitude photometric variations ($\Delta m_R \sim 0.4$ mag). The PDM periodogram for (79983) 1999 DF9 is shown in Figure 5. The best-fit period is $P = 6.65$ hr, which corresponds to a double-peak light curve (Fig. 6). Other PDM minima are found close to $P/2 \approx 3.3$ hr and 9.2 hr, a 24 hr alias of the best period. Phasing the data with P/2 results in a worse fit because the two minima of the double-peaked light curve exhibit significantly different morphologies (Fig. 6); the peculiar sharp feature superimposed on the brighter minimum, which is reproduced on two different nights, may be caused by a nonconvex feature on the surface of the KBO (Torppa et al. 2003). Period $P = 6.65$ hr was selected in 65 of the 100 Monte Carlo replications of the data set (see § 3.2). The second most selected solution (15%) was at $P = 9$ hr. We use $P = 6.65$ hr for the rest of the paper. The amplitude of the light curve, estimated as described in § 3.3, is $\Delta m_R = 0.40 \pm 0.02$ mag.

4.3. 2001 CZ$_{31}$

This object shows substantial brightness variations ($4.5 \sigma$ above the comparison stars) in a systematic manner. The first night of data seems to sample nearly one complete rotational phase. As for (35671) 1998 SN$_{165}$, the 2001 CZ$_{31}$ data span only two nights of observations. In this case, however, the PDM minima (see Figs. 7a and 7b) are very narrow, and only two correspond to independent periods, $P = 4.69$ hr (the minimum at 5.82 is a 24 hr alias of 4.69 hr), and $P = 5.23$ hr.

The amplitude obtained using the Monte Carlo method described in § 3.3 is $\Delta n = 0.16 \pm 0.01$ mag. This value was calculated using only our data, but it did not change when recalculated adding the PDR02 data.

### TABLE 8

**Relative Photometry Measurements of 2001 CZ$_{31}$**

| UT Date$^a$ | Julian Date$^b$ | $\Delta m_R$ (mag) |
|------------|----------------|-------------------|
| 2001 Feb 28.92789 | 2,451,969.42789 | 0.03 ± 0.05 |
| 2001 Feb 28.93903 | 2,451,969.43900 | 0.06 ± 0.04 |
| 2001 Feb 28.95013 | 2,451,969.45013 | 0.03 ± 0.04 |
| 2001 Feb 28.96120 | 2,451,969.46120 | 0.09 ± 0.04 |
| 2001 Feb 28.97235 | 2,451,969.47235 | −0.10 ± 0.04 |
| 2001 Feb 28.98349 | 2,451,969.48349 | −0.12 ± 0.04 |
| 2001 Feb 28.99475 | 2,451,969.49475 | 0.03 ± 0.04 |
| 2001 Mar 1.00706 | 2,451,971.50706 | −0.02 ± 0.03 |
| 2001 Mar 1.01817 | 2,451,971.51817 | 0.00 ± 0.03 |
| 2001 Mar 1.02933 | 2,451,971.52933 | 0.03 ± 0.03 |
| 2001 Mar 1.04046 | 2,451,971.54046 | 0.07 ± 0.04 |
| 2001 Mar 1.05153 | 2,451,971.55153 | 0.10 ± 0.04 |
| 2001 Mar 1.06304 | 2,451,971.56304 | 0.06 ± 0.04 |
| 2001 Mar 1.08608 | 2,451,971.58608 | −0.05 ± 0.04 |
| 2001 Mar 1.09808 | 2,451,971.59808 | −0.05 ± 0.05 |
| 2001 Mar 3.01239 | 2,451,971.51239 | 0.15 ± 0.05 |
| 2001 Mar 3.02455 | 2,451,971.52455 | −0.01 ± 0.05 |
| 2001 Mar 3.03596 | 2,451,971.53596 | 0.00 ± 0.04 |
| 2001 Mar 3.04731 | 2,451,971.54731 | −0.02 ± 0.03 |
| 2001 Mar 3.05865 | 2,451,971.55865 | −0.08 ± 0.04 |
| 2001 Mar 3.07060 | 2,451,971.57060 | −0.04 ± 0.04 |
| 2001 Mar 3.08212 | 2,451,971.58212 | 0.01 ± 0.03 |

$^a$ UT date at the start of the exposure.  
$^b$ Julian Date at the start of the exposure.  
$c$ Mean-subtracted apparent red magnitude; errors include uncertainties in relative and absolute photometry added quadratically.

### FIG. 2

Stacked histograms of the frame-to-frame variance (in magnitudes) in the optical data on the reference stars (white), comparison stars (gray), and the KBO (black). In (c), (e), and (j) the KBO shows significantly more variability than the comparison stars, whereas in all other cases it falls well within the range of photometric uncertainties of the stars of similar brightness.

### TABLE 9

**Light-Curve Properties of Observed KBOs**

| Object | $m_R$ (mag) | $\Delta m_R$ (mag) | $p^d$ (hr) |
|--------|------------|-------------------|----------|
| (35671) 1998 SN$_{165}$ | 21.20 ± 0.05 | 2 (1) | 0.16 ± 0.01 | 8.84 (8.70) |
| (79983) 1999 DF9 | 22.00 ± 0.05 | 3 | 0.40 ± 0.02 | 6.65 (9.00) |
| 2001 CZ$_{31}$ | 21.26 ± 0.06 | 2 (1) | 0.21 ± 0.02 | 4.71 (5.23) |
| (19308) 1996 TO$_{66}$ | 21.76 ± 0.05 | 3 | < 0.15 | ... |
| (19521) Chaos | 20.74 ± 0.06 | < 2 | 0.10 | ... |
| (80806) 2000 CM$_{105}$ | 21.26 ± 0.06 | 3 | < 0.14 | ... |
| (66652) 1999 RZ$_{535}$ | 21.76 ± 0.05 | < 3 | < 0.05 | ... |
| (47171) 1999 TC$_{36}$ | 21.26 ± 0.06 | < 3 | < 0.07 | ... |
| (38628) Huya | 21.26 ± 0.06 | < 3 | < 0.04 | ... |

$^a$ Mean red magnitude. Errors include uncertainties in relative and absolute photometry added quadratically.  
$^b$ Number of nights with useful data. Numbers in parentheses indicate number of nights of data from other observers used for period determination.  
$^c$ Light-curve amplitude.  
$^d$ Light-curve period (values in parentheses indicate less likely solutions not entirely ruled out by the data).
KBO 2001 CZ31 had also been observed by SJ02 in 2001 February and April, with inconclusive results. We used their data to try to rule out one (or both) of the two periods we found. We mean-subtracted the SJ02 data in order to combine them with our uncalibrated observations. Figure 7c shows the section of the periodogram around $P = 5$ hr, recalculated using SJ02’s first night plus our own data. The aliases are due to the 1 month time difference between the two observing runs. The new PDM minimum is at $P = 4.71$ hr—very close to the $P = 4.69$ hr determined from our data alone.

Visual inspection of the combined data set phased with $P = 4.71$ hr shows a very good match between SJ02’s first night (2001 February 20) and our own data (see Fig. 8). SJ02’s second and third nights show very large scatter and were not included in our analysis. Phasing the data with $P = 5.23$ hr yields a more scattered light curve, which confirms the PDM result. The Monte Carlo test for uniqueness yielded $P = 4.71$ hr as the best-fit period in 57% of the cases, followed by $P = 5.23$ hr in 21%, and a few other solutions, all below 10%, between $P = 5$ and 6 hr. We use $P = 4.71$ hr throughout the rest of the paper.

We measured a light-curve amplitude of $\Delta m = 0.21 \pm 0.02$ mag. If we use both ours and SJ02’s first night data, $\Delta m$ rises to 0.22 mag.

4.4. Flat Light Curves

The fluctuations detected in the optical data on KBOs (19308) 1996 TO66, 1996 TS66, (47171) 1999 TC36, (66652) 1999 RZ253, (80806) 2000 CM105, and (38628) Huya are well within the uncertainties. The KBO (19521) Chaos shows some variations with respect to the comparison stars but no period was found to fit all the data. See Table 9 and Figure 9 for a summary of the results.

4.5. Other Light-Curve Measurements

The KBO light-curve database has increased considerably in the last few years, largely due to the observational campaign of SJ02, with recent updates in Sheppard & Jewitt (2003, 2004). These authors have published observations and rotational data for a total of 30 KBOs (their SJ02 paper includes data for three other previously published light curves in the analysis). Other recently published KBO light curves include those for (50000) Quaoar (Ortiz et al. 2003) and the scattered KBO (29981) 1999 TD10 (Rousselot et al. 2003). Of the 10 KBO light curves presented in this paper, 6 are new to the database, bringing the total

![Fig. 3.—Periodogram for the data on (35671) 1998 SN165. Panel b shows an enlarged section near the minimum, calculated using only the data published in this paper, and panel c shows the same region recalculated after adding the PDR02 data.](image1)

![Fig. 4.—Light curve of (35671) 1998 SN165. The figure represents the data phased with the best-fit period $P = 8.84$ hr. Different symbols correspond to different nights of observation. The gray line is a second-order Fourier series fit to the data. The PDR02 data are shown as crosses.](image2)

![Fig. 5.—Periodogram for the (79983) 1999 DF9 data. The minimum corresponds to a light-curve period $P = 6.65$ hr.](image3)

![Fig. 6.—Same as Fig. 4, but for KBO (79983) 1999 DF9. The best-fit period is $P = 6.65$ hr. The lines represent second-order (solid line) and fifth-order (dashed line) Fourier series fits to the data. The normalized $\chi^2$ values of the fits are 2.8 and 1.3, respectively.](image4)
to 41. Table 10 lists the rotational data on the 41 KBOs that are analyzed in the rest of the paper.

5. ANALYSIS

In this section we examine the light-curve properties of KBOs and compare them with those of main-belt asteroids (MBAs). The light-curve data for these two families of objects cover different size ranges. MBAs, being closer to Earth, can be observed down to much smaller sizes than KBOs; in general it is very difficult to obtain good-quality light curves for KBOs with diameters \( D < 50 \) km. Furthermore, some KBOs surpass the 1000 km barrier, whereas the largest asteroid, Ceres, does not reach 900 km. This is taken into account in the analysis.

The light-curve data for asteroids were taken from the Harris Light Curve Catalog, version 5, while the diameter data were obtained from the Lowell Observatory database of asteroid orbital elements. The sizes of most KBOs were calculated from their absolute magnitude assuming an albedo of 0.04. The exceptions are (47171) 1999 TC36, (38638) Huya, (28978) Ixion, (55636) 2002 TX36, (66652) 1999 RZ36, (26308) 1998 SM165, and (20000) Varuna, for which the albedo has been shown to be inconsistent with the value 0.04 (Grundy et al. 2005). For example, in the case of (20000) Varuna simultaneous thermal and optical observations have yielded a red geometric albedo of 0.070 ± 0.030 / 0.017 (Jewitt et al. 2001).

5.1. Spin Period Statistics

As Figure 10 shows, the spin period distributions of KBOs and MBAs are significantly different. Because the sample of KBOs of small size or large periods is poor, to avoid bias in our comparison we consider only KBOs and MBAs with diameter larger than 200 km and with periods below 20 hr. In this range the mean rotational periods of KBOs and MBAs are 9.23 and 6.48 hr, respectively, and the two are different with a 98.5% confidence according to Student's \( t \)-test. However, the different means do not rule out that the underlying distributions are the same, and could simply mean that the two sets of data sample the same

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Fig. 7.—Periodogram for the 2001 CZ31 data. Panel b shows an enlarged section near the minimum, calculated using only the data published in this paper, and panel c shows the same region recalculated after adding the SJ02 data.

Fig. 8.—Same as Fig. 4, but for KBO 2001 CZ31. The data are phased with period \( P = 4.71 \) hr. The points represented by crosses are taken from SJ02.

Fig. 9.—"Flat" light curves. The respective amplitudes are within the photometric uncertainties.

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See http://pdssbn.astro.umd.edu/sbnhtml/asteroids/colors...lc.html.

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Available at ftp://ftp.lowell.edu/pub/elgb/astorb.html.
distribution differently. This is not the case, however, according to the Kolmogorov-Smirnov (K-S) test, which gives a probability that the periods of KBOs and MBAs are drawn from the same parent distribution of 0.7%.

Although it is clear that KBOs spin slower than asteroids, it is not clear why this is so. If collisions have contributed as significantly to the angular momentum of KBOs as they did for MBAs (Farinella et al. 1982; Catullo et al. 1984), then the observed difference should be related to how these two families react to collision events. We will address the question of the collisional evolution of KBO spin rates in a future paper.

5.2. Light-Curve Amplitudes and the Shapes of KBOs

The cumulative distribution of KBO light-curve amplitudes is shown in Figure 11. It rises very steeply in the low amplitude range ($\Delta m < 0.15$ mag) and then becomes shallower reaching

| Object Class$^a$ | Size$^b$ (km) | $P^c$ (hr) | $\Delta m_8^d$ (mag) | References |
|------------------|-------------|------------|----------------------|------------|
| KBOs Considered to Have $\Delta m < 0.15$ mag |
| (15789) 1993 SC | P           | 240        | 0.04                 | 2, 7       |
| (15820) 1994 TB | P           | 220        | <0.04                | 10        |
| (26181) 1996 GQ | S           | 730        | <0.10                | 10        |
| (15874) 1996 TL | S           | 480        | 0.06                 | 4, 7       |
| (15875) 1996 TP | P           | 250        | 0.12                 | 1, 7       |
| (79360) 1997 CS | C           | 630        | <0.08                | 10        |
| (91133) 1998 H  | P           | 170        | <0.15                | 10        |
| (33340) 1998 VG | P           | 280        | <0.10                | 10        |
| (19521) 1999 D  | C           | 600        | <0.10                | 10, 13     |
| (26375) 1999 DE | S           | 700        | <0.10                | 10        |
| (47171) 1999 TC | Pb          | 300        | <0.07                | 11, 13     |
| (55636) 2002 TX | C           | 710        | 0.08 ± 0.02          | 11        |
| (55637) 2002 UX | C           | 1090       | <0.10                | 11        |
| (55638) 2002 VE | P           | 500        | <0.10                | 11        |
| (55639) 2002 CM | C           | 330        | <0.14                | 13        |
| (66652) 1999 R  | Cb          | 170        | <0.05                | 13        |
| (996) 1996 TS  | C           | 300        | <0.14                | 13        |

| KBOs Considered to Have $\Delta m \geq 0.15$ mag |
|-----------------------------------------------|
| (32929) 1995 QY | P           | 180        | 0.60 ± 0.04          | 7, 10      |
| (24835) 1995 SM | C           | 630        | 0.19 ± 0.05          | 11        |
| (19308) 1996 TO | C           | 720        | 0.26 ± 0.03          | 3, 11      |
| (26308) 1998 SM | R           | 240        | 0.45 ± 0.03          | 8, 10      |
| (33128) 1998 BU | S           | 210        | 0.68 ± 0.04          | 8, 10      |
| (40314) 1999 KR | C           | 400        | 0.18 ± 0.04          | 10        |
| (47932) 2000 GN | C           | 360        | 0.61 ± 0.03          | 10        |
| (20000) Varuna| C           | 980        | 0.42 ± 0.03          | 10        |
| (2003) AZ    | P           | 900        | 0.14 ± 0.03          | 11        |
| (2001) QG    | Pcb         | 240        | 1.14 ± 0.04          | 12        |
| (50000) Quaoar| C           | 1300       | 0.17 ± 0.02          | 6         |
| (29981) 1999 TD | S           | 100        | 0.53 ± 0.03          | 9         |
| (35671) 1998 SN | C           | 400        | 0.16 ± 0.01          | 13        |
| (79983) 1999 DF | C           | 340        | 0.40 ± 0.02          | 13        |
| (2001) CZ   | C           | 440        | 0.21 ± 0.06          | 13        |

References.—(1) Collander-Brown et al. 1999; (2) Davies et al. 1997; (3) Hainaut et al. 2000; (4) Luu & Jewitt 1998; (5) Ortiz et al. 2001; (6) Ortiz et al. 2003; (7) Romanishin & Tegler 1999; (8) Romanishin et al. 2001; (9) Rousselot et al. 2003; (10) Sjoberg & Jewitt 2003; (11) Sheppard & Jewitt 2004; (12) Sheppard & Jewitt 2004; (13) this work.

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>a Dynamical class (C = classical KBO, P = Plutino, R = 2:1 resonant, S = scattered KBO, b = binary KBO, c = contact binary).

>b Diameter assuming an albedo of 0.04 except when measured (see text).

c Period of the light curve. For KBOs with both single- and double-peaked possible light curves the double-peaked period is listed.

d Light-curve amplitude.
large amplitudes. In quantitative terms, \(~70\%\) of the KBOs possess \(\Delta m < 0.15\) mag, while \(~12\%\) possess \(\Delta m \geq 0.40\) mag, with the maximum value being \(\Delta m = 0.68\) mag. (Fig. 11 does not include the KBO 2001 QG298, which has a light-curve amplitude \(\Delta m = 1.14 \pm 0.04\) mag and would further extend the range of amplitudes. We do not include 2001 QG298 in our analysis because it is thought to be a contact binary [Sheppard & Jewitt 2004].) Figure 11 also compares the KBO distribution to that of MBAs. The distributions of the two populations are clearly distinct; there is a larger fraction of KBOs in the low-amplitude range (\(\Delta m < 0.15\) mag) than in the case of MBAs, and the KBO distribution extends to larger values of \(\Delta m\).

Figure 12 shows the light-curve amplitude of KBOs and MBAs plotted against size. KBOs with diameters larger than \(D = 400\) km seem to have lower light-curve amplitudes than KBOs with diameters smaller than \(D = 400\) km. Student’s \(t\)-test confirms that the mean amplitudes in each of these two size ranges are different at the 98.5\% confidence level. For MBAs the transition is less sharp and seems to occur at a smaller size (\(D \sim 200\) km).

In the case of asteroids, we take the accepted explanation is that small bodies (\(D \leq 100\) km) are fragments of high-velocity impacts, whereas their larger counterparts (\(D > 200\) km) generally are not (Catullo et al. 1984). The light-curve data on small KBOs are still too sparse to permit a similar analysis. In order to reduce the effects of bias related to body size, we can consider only those KBOs and MBAs with diameters larger than 200 km. In this size range, 25 of 37 KBOs (69\%) and 10 of 27 MBAs (37\%) have light-curve amplitudes below 0.15 mag. We used the Fisher exact test to calculate the probability that such a contingency table would arise if the light-curve amplitude distributions of KBOs and MBAs were the same: the resulting probability is 0.8\%.

The distribution of light-curve amplitudes can be used to infer the shapes of KBOs, if certain reasonable assumptions are made (see, e.g., LL03). Generally, objects with elongated shapes produce large brightness variations due to their changing projected cross section as they rotate. Conversely, round objects, or those with the spin axis aligned with the line of sight, produce little or no brightness variations, resulting in “flat” light curves. Figure 12 shows that the light-curve amplitudes of KBOs with diameters smaller and larger than \(D = 400\) km are significantly different. Does this mean that the shapes of KBOs are also different in these two size ranges? To investigate this possibility of a size dependence among KBO shapes we consider KBOs with diameters smaller and larger than 400 km separately. We loosely refer to objects with diameter \(D > 400\) km and \(D \leq 400\) km as larger and smaller KBOs, respectively.

We approximate the shapes of KBOs by triaxial ellipsoids with semi-axes \(a > b > c\). For simplicity we consider the case in which \(b = c\) and use the axis ratio \(\bar{a} = a/b\) to characterize the shape of an object. The orientation of the spin axis is parameterized by the aspect angle \(\theta\), defined as the smallest angular distance between the line of sight and the spin vector. On this basis the light-curve amplitude \(\Delta m\) is related to \(\bar{a}\) and \(\theta\) via the relation (eq. [2] of LL03a with \(\bar{c} = 1\))

\[
\Delta m = 2.5 \log \sqrt{\frac{2\bar{a}^2}{1 + \bar{a}^2 + (\bar{a}^2 - 1) \cos 2\theta}}
\]

(1)

Following LL03b we model the shape distribution by a power law of the form

\[
f(\bar{a}) \, d\bar{a} \propto \bar{a}^{-\eta} \, d\bar{a},
\]

(2)

where \(f(\bar{a}) d\bar{a}\) represents the fraction of objects with shapes between \(\bar{a}\) and \(\bar{a} + d\bar{a}\). We use the measured light-curve amplitudes

\[\text{Fig. 10.—Histograms of the spin periods of KBOs (top) and MBAs (bottom) satisfying \(D > 200\) km, \(\Delta m \geq 0.15\) mag, and \(P < 20\) hr. The mean rotational periods of KBOs and MBAs are 9.23 and 6.48 hr, respectively. The y-axis in both cases indicates the number of objects in each range of spin periods.}

\[\text{Fig. 11.—Cumulative distribution of light-curve amplitude for KBOs (circles) and MBAs (crosses) larger than 200 km. We plot only KBOs for which a period has been determined. KBO 2001 QG298, thought to be a contact binary (Sheppard & Jewitt 2004), is not plotted, although it may be considered an extreme case of elongation.}

\[\text{Fig. 12.—Light-curve amplitudes of KBOs (circles) and MBAs (crosses) plotted against object size.}\]
to estimate the value of $q$ by employing both the method described in LL03a and by Monte Carlo fitting the observed amplitude distribution (SJ02; LL03b). The latter consists of generating artificial distributions of $\Delta m$ (eq. [1]) with values of $\tilde{a}$ drawn from distributions characterized by different $q$-values (eq. [2]), and selecting the one that best fits the observed cumulative amplitude distribution (Fig. 11). The values of $\theta$ are generated assuming random spin axis orientations. We use the K-S test to compare the different fits. The errors are derived by bootstrap resampling the original data set (Efron 1979) and measuring the dispersion in the distribution of best-fit power-law indices, $q$, found for each bootstrap replication.

Following the LL03a method we calculate the probability of finding a KBO with $\Delta m \geq 0.15 \text{ mag}$:

$$p(\Delta m \geq 0.15) \approx \int_{\tilde{a}^{\text{min}}}^{\tilde{a}^{\text{max}}} f(\tilde{a}) \sqrt{\frac{\tilde{a}^2 - K}{(\tilde{a}^2 - 1)K}} d\tilde{a},$$

where $K = 10^{0.8 \times 0.15}$, $f(\tilde{a}) = C \tilde{a}^{-q}$, and $C$ is a normalization constant. This probability is calculated for a range of $q$-values to determine the one that best matches the observed fraction of light curves with amplitude larger than 0.15 ma. These fractions are $f(\Delta m \geq 0.15 \text{ mag}; D \leq 400 \text{ km}) = 8/19, f(\Delta m \geq 0.15 \text{ mag}; D > 400 \text{ km}) = 5/21$, and $f(\Delta m \geq 0.15 \text{ mag}) = 13/40$ for the complete set of data. The results are summarized in Table 11 and shown in Figure 13.

The uncertainties in the values of $q$ obtained using the LL03a method ($q = 4.3^{+2.0}_{-1.6}$ for KBOs with $D \leq 400 \text{ km}$ and $q = 7.4^{+3.1}_{-2.4}$ for KBOs with $D > 400 \text{ km}$; see Table 11) do not rule out similar shape distributions for smaller and larger KBOs. This is not the case for the Monte Carlo method. The reason for this is that the LL03a method relies on a single, more robust parameter: the fraction of light curves with detectable variations. The sizeable error bar is indicative that a larger data set is needed to better constrain the values of $q$. In any case, it is reassuring that both methods yield steeper shape distributions for larger KBOs, implying more spherical shapes in this size range. A distribution with $q \approx 8$ predicts that $\sim 75\%$ of the large KBOs have $a/b < 1.2$. For the smaller objects we find a shallower distribution, $q \sim 4$, which implies a significant fraction of very elongated objects: $\sim 20\%$ have $a/b > 1.7$. Although based on small numbers, the shape distribution of large KBOs is well fitted by a simple power law (the K-S rejection probability is 0.6%). This is not the case for smaller KBOs, for which the fit is poorer (K-S rejection probability is 20%; see Fig. 13). Our results are in agreement with previous studies of the overall KBO shape distribution, which had already shown that a simple power law does not explain the shapes of KBOs as a whole (LL03b; SJ02).

The results presented in this section suggest that the shape distributions of smaller and larger KBOs are different. However, the existing number of light curves is not enough to make this difference statistically significant. When compared to asteroids, KBOs show a preponderance of low-amplitude light curves, possibly a consequence of their possessing a larger fraction of nearly spherical objects. It should be noted that most of our analysis assumes that the light-curve sample used is homogeneous and unbiased; this is probably not true. Different observing conditions, instrumentation, and data analysis methods introduce systematic uncertainties in the data set. However, the most likely source of bias in the sample is that some flat light curves may not have been published. If this is the case, our conclusion that the amplitude distributions of KBOs and MBAs are different would be strengthened. On the other hand, if most unreported nondetections correspond to smaller KBOs then the inferred contrast in the shape distributions of different-sized KBOs would be less significant. Clearly, better observational constraints, particularly of smaller KBOs, are necessary to constrain the KBO shape distribution and understand its origin.

5.3. The Inner Structure of KBOs

In this section we wish to investigate if the rotational properties of KBOs show any evidence that they have a rubble pile structure; a possible dependence on object size is also investigated. As in the case of asteroids, collisional evolution may have played an important role in modifying the inner structure of KBOs. Large asteroids ($D \gtrsim 200 \text{ km}$) have in principle survived collisional destruction for the age of the solar system, but may nonetheless have been converted to rubble piles by repeated impacts. As a result of multiple collisions, the “loose” pieces of the larger asteroids would have reassembled into shapes close to triaxial equilibrium ellipsoids (Farinella et al. 1981). Instead, the shapes of the smaller asteroids ($D \lesssim 100 \text{ km}$) are consistent with collisional fragments (Catullo et al. 1984), indicating that they are most likely by-products of disruptive collisions.

### Table 11

| Size Range | Method | LL03 | MC |
|------------|--------|------|----|
| $D \leq 400 \text{ km}$ | $4.3^{+2.0}_{-1.6}$ | $3.8 \pm 0.8$ |
| $D > 400 \text{ km}$ | $7.4^{+3.1}_{-2.4}$ | $8.0 \pm 1.4$ |
| All sizes | $5.7^{+1.6}_{-1.3}$ | $5.3 \pm 0.8$ |

*a* Range of KBO diameters, considered in each case.

*b* LL03 is the method described in LL03a, and MC is a Monte Carlo fit of the light-curve amplitude distribution.
The latter is calculated from the equilibrium shapes of gravitationally bound bodies (Benz & Asphaug 1999), the model results should apply to other sizes. Clearly, the LRQ00 model makes several specific assumptions and represents one possible idealization of what is usually referred to as “a rubble pile.” Nevertheless, the results are illustrative of how collisions may affect this type of structure and are useful for comparison with the KBO data.

Figure 14 plots the light-curve amplitudes versus spin periods for the 15 KBOs whose light-curve amplitudes and spin periods are known. Open and filled symbols indicate the KBOs with diameters smaller and larger than $D = 400$ km, respectively. Clearly, the smaller and larger KBOs occupy different regions of the diagram. For the larger KBOs (black filled circles) the (small) light-curve amplitudes are almost independent of the objects’ spin periods. In contrast, smaller KBOs span a much broader range of light-curve amplitudes. Two objects have very low amplitudes: (35671) 1998 SN$_{165}$ and 1999 KR$_{16}$, which have diameters $D \approx 400$ km and fall precisely on the boundary of the two size ranges. The remaining objects hint at a trend of increasing light-curve amplitudes that would be generated by such remnants (assuming that they are observed equator-on) are plotted in Figure 14 as gray circles. Note that, although the simulated rubble piles have radii of 1 km, since the effects of the collision scale with the ratio of impact energy to gravitational binding energy of the colliding bodies (Benz & Asphaug 1999), the model results should apply to other sizes. Clearly, the LRQ00 model makes several specific assumptions and represents one possible idealization of what is usually referred to as “a rubble pile.” Nevertheless, the results are illustrative of how collisions may affect this type of structure and are useful for comparison with the KBO data.

The light-curve amplitudes resulting from the LRQ00 experiment are relatively small ($\Delta m < 0.25$ mag) for spin periods larger than $P \sim 5.5$ hr (see Fig. 14). Objects spinning faster than $P = 5.5$ hr have more elongated shapes, resulting in larger light-curve amplitudes, up to 0.65 mag. The latter are the result of collisions with higher angular momentum transfer than the former (see Table 1 of LRQ00). The maximum spin rate attained by the rubble piles, as a result of the collision, is $\sim 4.5$ hr. This is consistent with the maximum spin expected for bodies in hydrostatic equilibrium with the same density as the rubble piles ($\rho = 2000$ kg m$^{-3}$; see Fig. 14, long-dashed line). The results of LRQ00 show that collisions between ideal rubble piles can produce elongated remnants (when the projectile brings significant angular momentum into the target), and that the spin rates of the collisional remnants do not extend much beyond the maximum spin permitted to fluid uniform bodies with the same bulk density.

The distribution of KBOs in Figure 14 is less clear. Indirect estimates of KBO bulk densities indicate values $\rho \sim 1000$ kg m$^{-3}$ (Luu & Jewitt 2002). If KBOs are strengthless rubble piles with such low densities, we would not expect to find objects with spin periods lower than $P \sim 6$ hr (Fig. 14, short-dashed line). However, one object (2001 CZ$_{23}$) is found to have a spin period below 5 hr. If this object has a rubble pile structure, its density must be at least $\sim 2000$ kg m$^{-3}$. The remaining 14 objects have spin periods below the expected upper limit, given their estimated density. Of the 14, 4 objects lie close to the line corresponding to equilibrium ellipsoids of density $\rho = 1000$ kg m$^{-3}$. One of these objects, (20000) Varuna, has been studied in detail by SJ02. The authors conclude that (20000) Varuna is best interpreted as a rotationally deformed rubble pile with $\rho \leq 1000$ kg m$^{-3}$. One object, 2001 QG$_{398}$, has an exceptionally large light-curve amplitude ($\Delta m = 1.14$ mag), indicative of a very elongated shape (axis ratio $a/b > 2.85$), but given its modest spin rate ($P = 13.8$ hr) and approximate size ($D \sim 240$ km) it is unlikely that it would be able to keep such an elongated shape against the crush of gravity. Analysis of the light curve of this object (Sheppard & Jewitt 2004) suggests that it is a close/contact binary KBO. The same applies to two other KBOs, 2000 GN$_{71}$ and (33128) 1998 BU$_{48}$, also very likely to be contact binaries.

To summarize, it is not clear that KBOs have a rubble pile structure, based on their available rotational properties. A comparison with computer simulations of rubble pile collisions shows...
that larger KBOs ($D > 400$ km) occupy the same region of the period-amplitude diagram as the LRO90 results. This is not the case for most of the smaller KBOs ($D \leq 400$ km), which tend to have larger light-curve amplitudes for similar spin periods. If most KBOs are rubble piles then their spin rates set a lower limit to their bulk density: one object (2001 CZ$_{31}$) spins fast enough that its density must be at least $\rho \sim 2000$ kg m$^{-3}$, while four other KBOs [including (20000) Varuna] must have densities larger than $\rho \sim 1000$ kg m$^{-3}$. A better assessment of the inner structure of KBOs will require more observations and detailed modeling of the collisional evolution of rubble piles.

6. CONCLUSIONS

We have collected and analyzed $R$-band photometric data for 10 Kuiper Belt objects, 5 of which have not been studied before. No significant brightness variations were detected from KBOs (80806) 2000 CM$_{106}$, (66652) 1999 RZ$_{253}$, and 1996 TS$_{66}$. Previously observed KBOs (19521) Chaos, (47171) 1999 TC$_{36}$, and (38628) Huya were confirmed to have low amplitude light curves ($\Delta m \leq 0.1$ mag). KBOs (35671) 1998 SN$_{165}$, (79983) 1999 DF$_{9}$, and 2001 CZ$_{31}$ were shown to have periodic brightness variations. Our light-curve amplitude statistics are thus: 3 out of 10 (30%) observed KBOs have $\Delta m \geq 0.15$ mag, and 1 out of 10 (10%) has $\Delta m \geq 0.40$ mag. This is consistent with previously published results.

The rotational properties that we obtained were combined with existing data in the literature, and the total data set was used to investigate the distribution of spin period and shapes of KBOs. Our conclusions can be summarized as follows:

1. KBOs with diameters $D > 200$ km have a mean spin period of 9.23 hr and thus rotate slower on average than main-belt asteroids of similar size ($P_M / \theta = 6.48$ hr). The probability that the two distributions are drawn from the same parent distribution is $0.7\%$, as judged by the K-S test.

2. Twenty-six of 37 KBOs (70%, $D > 200$ km) have light-curve amplitudes below 0.15 mag. In the asteroid belt only 10 of the 27 (37%) asteroids in the same size range have such low-amplitude light curves. This difference is significant at the 99.2% level according to the Fisher exact test.

3. KBOs with diameters $D > 400$ km have light curves with significantly (98.5% confidence) smaller amplitudes ($\langle \Delta m \rangle = 0.13$ mag) than KBOs with diameters $D \leq 400$ km ($\langle \Delta m \rangle = 0.25$ mag).

4. These two size ranges seem to have different shape distributions, but the few existing data do not render the difference statistically significant. Even though the shape distributions in the two size ranges are not inconsistent, the best-fit power-law solutions predict a larger fraction of round objects in the $D > 400$ km size range [$f(a/b < 1.2) \sim 70\%$] than in the group of smaller objects [$f(a/b < 1.2) \sim 42\%$].

5. The current KBO light-curve data are too sparse to allow a conclusive assessment of the inner structure of KBOs.

6. KBO 2001 CZ$_{31}$ has a spin period of $P = 4.71$ hr. If this object has a rubble pile structure, then its density must be $\rho \geq 2000$ kg m$^{-3}$. If the object has a lower density, then it must have internal strength.

The analysis presented in this paper rests on the assumption that the available sample of KBO rotational properties is homogeneous. However, in all likelihood the database is biased. The most likely bias in the sample comes from unpublished flat light curves. If a significant fraction of flat light curves remains unreported, then points 1 and 2 above could be strengthened, depending on the cause of the lack of brightness variation (slow spin or round shape). On the other hand, points 3 and 4 could be weakened if most unreported cases correspond to smaller KBOs. Better interpretation of the rotational properties of KBOs will greatly benefit from a larger and more homogeneous data set.

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