

THE SHAPES, DENSITIES, AND PHASE FUNCTIONS OF TRANS-NEPTUNIAN OBJECTS

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ABSTRACT

We present a systematic investigation of the rotational lightcurves of trans-Neptunian objects based on extensive optical data from Mauna Kea. Four of 13 objects (corresponding to 31%) in our sample ((33128) 1998 BU₄₈, 2000 GN₁₇₁, (20000) Varuna and (40314) 1999 KR₁₆) were found to exhibit lightcurves with peak-to-peak range ≥ 0.15 magnitude. In the sample 23% of the objects have lightcurve ranges ≥ 0.4 magnitudes. Curiously, the objects are very large (≥ 250 km diameter, assuming an albedo of 0.04) and, in the absence of rotation, should be near spherical due to self compression. We propose that the large amplitude, short period objects are rotationally distorted, low density rubble piles. Statistically, the trans-Neptunian objects are less spherical than their main-belt asteroid counterparts, indicating a higher specific angular momentum perhaps resulting from the formation epoch. In addition to the rotational lightcurves, we measured phase darkening for 7 Kuiper Belt objects in the 0 to 2 degree phase angle range. Unlike Pluto, the measured values show steep slopes consistent with backscatter from low albedo porous surface materials.

Sheppard (2002) and Sheppard and Jewitt (2002) for more details and Sheppard (2002) for an analysis of an additional 15 KBOs.

The apparent magnitude of a KBO depends on its physical and geometrical circumstances. The apparent brightness of an inert body viewed in reflected light will usually vary because of 1) changes in the observing geometry, including phase darkening and 2) rotational modulation of the scattered light including albedo and elongation characteristics.

The large amplitudes and fast rotations of (20000) Varuna, 2000 GN₁₇₁, and (33128) 1998 BU₄₈ suggest that the lightcurves are caused by elongation and not surface albedo features. In support of this is the finding that (33128) 1998 BU₄₈, (20000) Varuna and 2000 GN₁₇₁ show no color variations throughout their lightcurves. Independently 2000 GN₁₇₁ shows two distinct lightcurve maxima and minima which is a strong reason to believe the object is elongated. The other lightcurve we found was for (40314) 1999 KR₁₆. Since its amplitude is much smaller and period longer, the lightcurve of (40314) 1999 KR₁₆ may be more dominated by nonuniform albedo features on its surface, though we found no measurable color variation over the rotation.

1. RESULTS

We obtained voluminous time resolved photometric observations from the University of Hawaii 2.2 m diameter telescope from 1999 to 2001 to determine the rotational lightcurves, colors, and phase functions of Kuiper Belt objects (KBOs). As our sample, we select the intrinsically brightest (presumably largest) KBOs. Specifically, we observed KBOs having absolute magnitude $H_R \leq 7.5$, corresponding to $D \geq 200$ km if a red geometric albedo of $p_R = 0.04$ is assumed. Results of the lightcurve analysis on our initial 13 KBOs observed are summarized in Table 1 and some lightcurves shown in Figures 1, 2, 3, and 4. This report describes work already published or in press at The Astronomical Journal. See Jewitt and

2. DISCUSSION

Interestingly there is a group of asteroids that are large ($D = 200$ to 300 km) and which have substantial lightcurve amplitudes. They also possess fast rotations. These objects are probably rotationally deformed “rubble piles” which may be similar to a Jacobi ellipsoid type object (Farinella et al. 1981). Such rubble pile structures may form in the main asteroid belt because all objects have been effected by the high-velocity (~ 5 km/s) collisions that occur there (Farinella, Paolicchi, Zappala 1982). The effect of collisions is highly dependent on the object size. Objects with $D > 300$ km are large enough not to be completely turned into rubble piles or have their angular momentum greatly altered. Objects with di-

Table 1. Amplitudes and Periods of Observed KBOs.

Name	Δm_R (mag)	Single (hrs)	Double (hrs)
2000 EB ₁₇₃	< 0.06	-	-
Varuna	0.42 ± 0.03	-	6.34 ± 0.01
1999 DE ₉	< 0.10	> 12?	-
1996 GQ ₂₁	< 0.10	-	-
2000 GN ₁₇₁	0.61 ± 0.03	-	8.329 ± 0.005
Chaos	< 0.10	-	-
1998 VG ₄₄	< 0.10	-	-
2001 FZ ₁₇₃	< 0.06	-	-
1998 BU ₄₈	0.68 ± 0.04	4.9 ± 0.1 6.3 ± 0.1	9.8 ± 0.1 12.6 ± 0.1
1999 KR ₁₆	0.18 ± 0.04	5.929 ± 0.001 5.840 ± 0.001	11.858 ± 0.002 11.680 ± 0.002
1997 CS ₂₉	< 0.08	-	-
2001 CZ ₃₁	< 0.20	?	?
1998 HK ₁₅₁	< 0.15	-	-

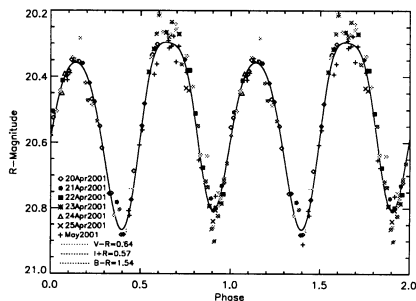


Figure 1. The phased data from the UT April 20–25 and May 11–13, 2001 observations of 2000 GN₁₇₁. The period has been phased to 8.329 hours which is the best fit double-peaked period. The May data have been corrected for geometry and phase angle differences relative to the April data. No color variation is seen within our uncertainties. A Fourier fit shows the two pronounced maxima and minima.

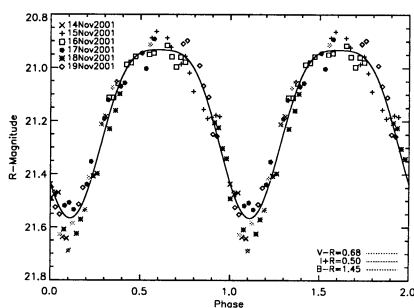


Figure 2. BVRI phased data from the UT November 14–19 observations of (33128) 1998 BU₄₈. The period has been phased to 6.29 hours which is one of the best fit single-peaked periods, the other being around 4.9 hours.

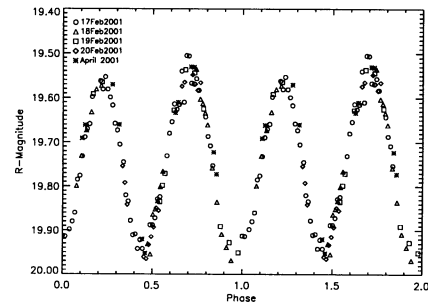


Figure 3. R-band data for 20000 Varuna phased to the double-peaked period of 6.34 hours.

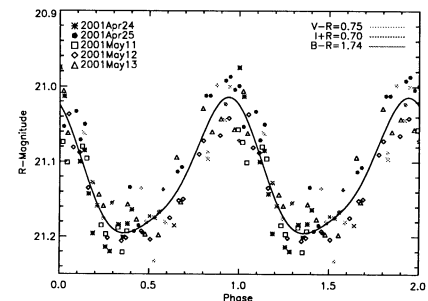


Figure 4. The phased BVRI data from the UT April 24–25 and May 11–13, 2001 observations of 1999 KR₁₆. The period has been phased to 5.840 hours which is one of the best fit single-peaked periods, the other being at 5.929 hours.

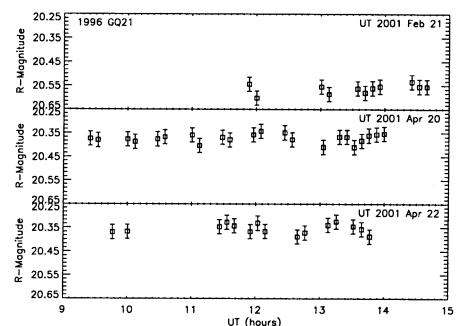


Figure 5. 1996 GQ₂₆ is one of the 9 KBOs found to have no significant variation.

ameters 200 to 300 km are large enough to be gravitationally bound but impacts over the age of the Solar System will transform them into rubble piles and may significantly change their angular momentum. Most asteroids with $D < 200$ km are thought to be fragments from catastrophic collisions and are not massive enough to be gravitationally spherical.

The fraction of KBOs in this survey with significant lightcurve variation is $f(\Delta m_R \geq 0.15) = \frac{4}{13}$ (31%) and $f(\Delta m_R \geq 0.40) = \frac{3}{13}$ (23%). In comparison to the percentages of KBOs with large amplitude lightcurves (> 0.40 or about 1.5 difference in brightness), main-belt asteroids with $D > 200$ km $f(\Delta m_R \geq 0.40) = \frac{5}{27}$ (19%) when their pole orientations are $\theta = 90$ degrees to our line of sight. With the average pole orientation of $\theta = 60$ degrees only (11%) ($f(\Delta m_R \geq 0.40) = \frac{3}{27}$) would have large amplitude lightcurves. These large amplitude lightcurve objects are thought to be the Jacobi ellipsoid type objects.

Figure 6 shows how the largest ($D > 200$ km) main belt asteroids compare with the KBOs. Many of the KBOs fall in the upper and upper left parts of this figure, where the Jacobi ellipsoids are encountered in the asteroid belt. The Student's t-test was used to measure the significance of the differences between the means of the asteroid and KBO periods and amplitudes. The mean periods are 5.56 ± 0.89 and 7.80 ± 1.20 hours for the asteroids and KBOs respectively, giving a t-statistic of -3.84 (12 degrees of freedom) which is significant at the 99.7% (3σ) confidence level. The KBOs have a larger mean amplitude, but the significance between the difference of means, 0.36 ± 0.11 vs. 0.50 ± 0.16 magnitudes for the asteroids and KBOs respectively, is only 95% (2σ) with a t-statistic of -1.83 . A plausible explanation for the differences between the two belts of objects is that the KBOs are very large yet structurally weak and of low density. This would allow many of the KBOs to be gravitationally bound rubble piles easily distorted by centripetal forces due to their rotation.

It appears that about 32% of KBOs are highly elongated and that there may be a large fraction of binary KBOs. Both the binaries and the highly elongated shapes indicate large specific angular momentum, most likely delivered by glancing collisions. The current rate of collisions is too small however for any substantial modifications of the spins or shapes of KBOs (Jewitt and Sheppard 2002). Instead, we prefer the hypothesis that the binaries and elongated shapes are products of an early, denser phase in the Kuiper Belt, perhaps associated with its formation.

2.1. Densities of KBOs

For each KBO that showed a nonflat lightcurve we found the minimum bulk density, ρ , required to maintain a stable configuration, as described in Jewitt and Sheppard (2002). We present new densities for five main belt asteroids calculated under the as-

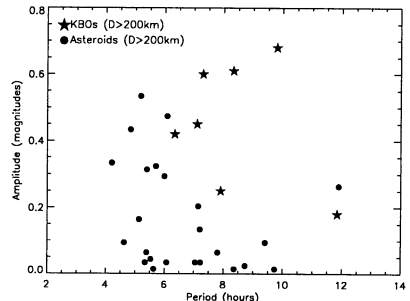


Figure 6. Rotational variability and periods of all the asteroids with diameters > 200 km and of Kuiper Belt objects in our sample. Objects in the upper and upper left portions of the graph are possibly rotationally deformed rubble piles. The asteroid amplitudes which were taken from pole orientations of 90 degrees have been corrected to a mean pole orientation at 60 degrees to better compare them with the KBOs of unknown orientation. KBOs with amplitudes ≤ 0.1 magnitudes and periods ≥ 12 hours are subject to observational bias against detection.

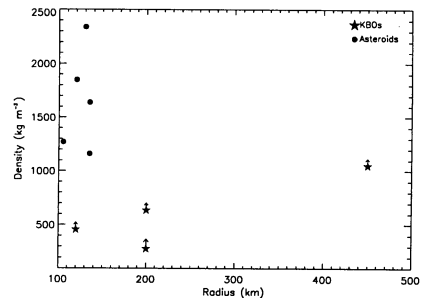


Figure 7. Size and densities of possible rotationally deformed KBOs and main belt asteroids. The asteroids have lower densities than expected for solid rock, but are still denser than the KBOs.

sumption that they are equilibrium rotational (Jacobi ellipsoid) figures. We used their lightcurves as seen at maximum amplitude, to eliminate the effects of projection. The densities are higher than those of the KBOs obtained using the same method (Figure 7) but lower than expected for solid rock. This provides another hint that these objects may be internally porous.

2.2. Phase Functions of KBOs

Seven of the KBOs were observed over a range of phase angles sufficient for us to measure the phase darkening. We plot the quantity $m_R(1, 1, \alpha) = m_R - 5 \log(R\Delta)$ against α for these 7 KBOs in Figure 8. The linear least squares fits to the KBO data are listed in Table 2 and shown in Figure 8. Within the uncertainties, we find that photometry of the 7

Table 2. Phase Function Data for KBOs.

Name	H	G	$\beta(\alpha < 2 \text{ deg})$
2000 EB ₁₇₃	4.44 ± 0.02	-0.15 ± 0.05	0.14 ± 0.02
Varuna	3.21 ± 0.05	-0.58 ± 0.10	0.19 ± 0.06
1999 DE ₉	4.53 ± 0.03	-0.44 ± 0.07	0.18 ± 0.06
1996 GQ ₂₁	4.47 ± 0.02	-0.04 ± 0.05	0.14 ± 0.03
2000 GN ₁₇₁	5.98 ± 0.02	-0.12 ± 0.05	0.14 ± 0.03
1999 KR ₁₆	5.37 ± 0.02	-0.08 ± 0.05	0.14 ± 0.02
2001 CZ ₃₁	5.53 ± 0.03	-0.05 ± 0.07	0.13 ± 0.04
MEAN	-	-0.21 ± 0.04	0.15 ± 0.01
Pluto	-1.00 ± 0.01	0.88 ± 0.02	0.0372 ± 0.0016

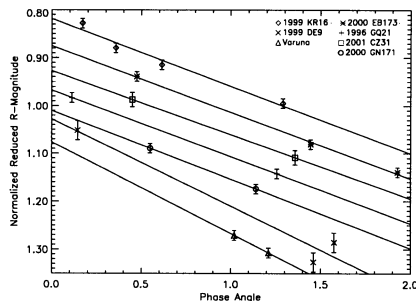


Figure 8. Phase functions for KBOs observed at several phase angles. The average linear fit gives a phase coefficient of $\beta(\alpha < 2 \text{ deg}) = 0.15 \text{ magnitudes per degree}$. Objects with more than two data points show evidence of the nonlinear opposition surge.

KBOs is compatible with $\beta(\alpha < 2 \text{ deg}) = 0.15 \pm 0.01 \text{ mag deg}^{-1}$. In contrast the phase function for Pluto was found to be linear throughout the 0 to 2 degrees phase angle range with $\beta(\alpha < 2 \text{ deg}) = 0.0372 \pm 0.0016 \text{ mag deg}^{-1}$.

The results of fits using the Bowell et al. (1989) $H - G$ formalism are presented in Table 2. The KBOs show steep slopes with a possible moderate opposition surge. The best-fit values of the G parameter are very low with an average of -0.21 . This small G value more closely resembles that of dark, C-type asteroids ($G \sim 0.15$) than the brighter, S-types ($G \sim 0.25$) in the main-belt. This is consistent with, though does not prove, the assumption that the majority of KBOs are of very low albedo. The similarity of the slopes of the phase functions of all KBOs in our sample suggests comparative uniformity of the surface compositions, physical states, and albedos. As a comparison, Pluto was found to have a best fit $G = 0.88 \pm 0.02$ using data from Tholen & Tedesco (1994). The dramatic difference between the backscattering phase functions of Pluto and the smaller KBOs studied here is shown in Figure 9. This difference is consistent with the smaller KBOs having low albedo (0.04?) surfaces qualitatively different from the high albedo (0.6), ice-covered surface of Pluto.

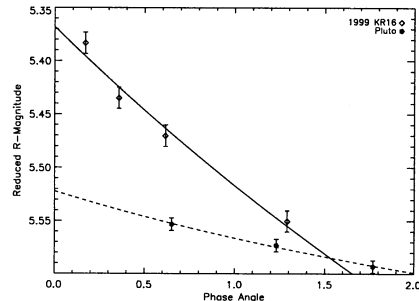


Figure 9. Comparison of phase functions for the typical KBO 1999 KR₁₆ and Pluto. The Solid line is the best fit Bowell et al. HG phase function for 1999 KR₁₆ with $G = -0.08$. Data points for Pluto are from Tholen & Tedesco (1994) and are offset in the vertical direction from reduced magnitude -1.0 . Pluto has a best fit $G = 0.88$ shown with the dashed line.

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