HAWAII KUIPER BELT VARIABILITY PROJECT: AN UPDATE

SCOTT S. SHEPPARD and DAVID C. JEWITT
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822, USA

Abstract. We have been systematically monitoring a large sample of bright Kuiper Belt objects for possible light variations due to rotational and phase angle effects. Here we report on three objects, 2003 AZ$_{84}$, (24835) 1995 SM$_{55}$ and (55636) 2002 TX$_{300}$ observed to have measurable rotational lightcurves with peak-to-peak amplitudes of 0.14 ± 0.03, 0.19 ± 0.05 and 0.08 ± 0.02 magnitudes and single-peaked periods of 6.71 ± 0.05, 4.04 ± 0.03 and 8.12 ± 0.08 hours, respectively. We observed a further ten objects which showed no rotational photometric variation within measurement uncertainties. In addition, we find that the lightcurve of 1995 SM$_{55}$ may have a variable amplitude. We discuss this peculiar object as well as our observations of the reportedly variable Kuiper Belt object (19308) 1996 TO$_{66}$. Finally, we continue to find the phase functions of the Kuiper Belt objects to be very steep and linear, to first order, with a median slope of 0.16 ± 0.01 magnitudes per degree in the phase angle range 0 to 2 degrees.

1. Introduction

The rotations and shapes of the KBOs are probably a function of their size. KBOs may be structurally weak bodies held together by gravity in a rubble pile type structure (Jewitt and Sheppard, 2002). The spins of the larger objects are probably primordial with little modification by post-formation impacts. The smaller objects are probably collisional fragments with sizes, shapes and spins determined at the moment of catastrophic break-up (Farinella and Davis, 1996). The vast majority of Kuiper Belt Objects (KBOs) currently can not be resolved at their large heliocentric distances ($\gtrsim$ 30 AU). Presently, the only feasible way to determine KBO shapes and surface features is by observing their light variations.

We are obtaining voluminous time resolved optical photometric observations to determine the rotational lightcurves and phase functions of KBOs. The University of Hawaii 2.2 meter telescope with its Tektronix 2048 × 2048 CCD was used for the observations (see section 2 of Sheppard and Jewitt (2002) for further observational and data reduction details). As our sample, we select the intrinsically brightest (presumably largest) KBOs. The 33 large KBOs ($\geq$ 200 km in diameter, assuming a low albedo) we have observed already exceed the number of asteroids of this size.

This short note is a continuation of Jewitt and Sheppard (2002) and Sheppard and Jewitt (2002) and a more detailed write-up will soon follow. The present work

Earth, Moon and Planets **92:** 207–219, 2003.

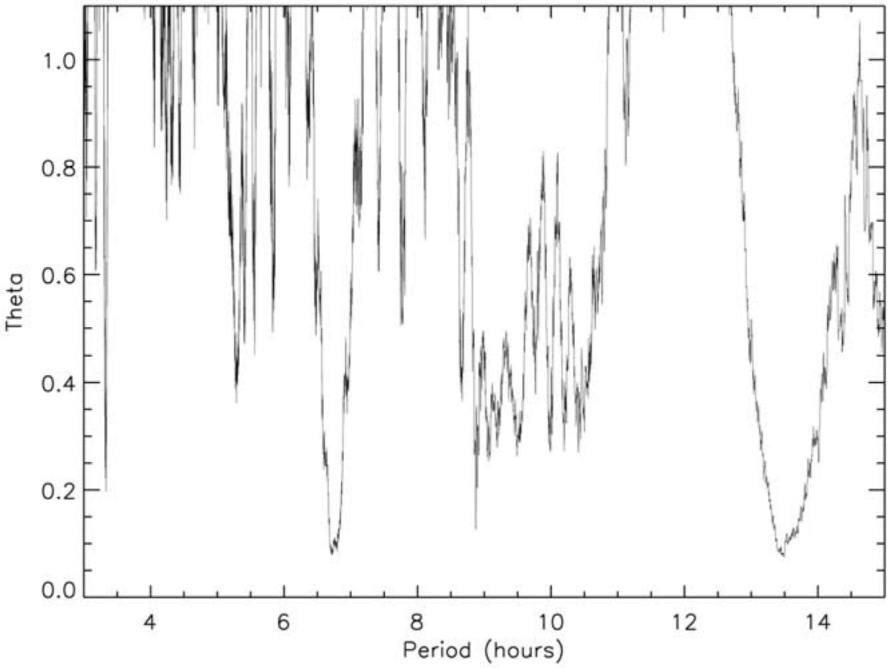

Figure 1. The phase dispersion minimization (PDM) plot for 2003 AZ$_{84}$. Best fits from this plot are the 6.72 hour single-peaked fit and the 13.44 hour double-peaked fit.

is intended as a timely pointer to a manuscript that is in preparation and our already published articles and is not a substitute for them.

2. Rotation Results

Rotational lightcurve analyses for the newly observed KBOs are shown in Table I and discussed below. We employed the phase dispersion minimization (PDM) method (Stellingwerf, 1978) to search for periodicity in the data. The best-fit period should have a very small normalized dispersion, Θ, compared with the unphased data, and thus $\Theta \ll 1$ indicates that a good fit has been found.

When combining the newly observed objects with our previous data (Sheppard and Jewitt, 2002) we find that 9 of 33 (27%) objects in our sample show peak-to-peak amplitudes ≥ 0.15 magnitudes while 15% have amplitudes $\geq$0.4 magnitudes and 9% have amplitudes ≥ 0.6 magnitudes. The large main-belt asteroids have a larger fraction of objects with amplitudes ≥ 0.15 magnitudes, a comparable fraction with amplitudes ≥ 0.4 magnitudes but a smaller fraction with amplitudes ≥ 0.6 magnitudes.

Please see Jewitt and Sheppard (2002) as well as Sheppard and Jewitt (2002) for further discussion on the interpretation of KBO light curves. The complete data

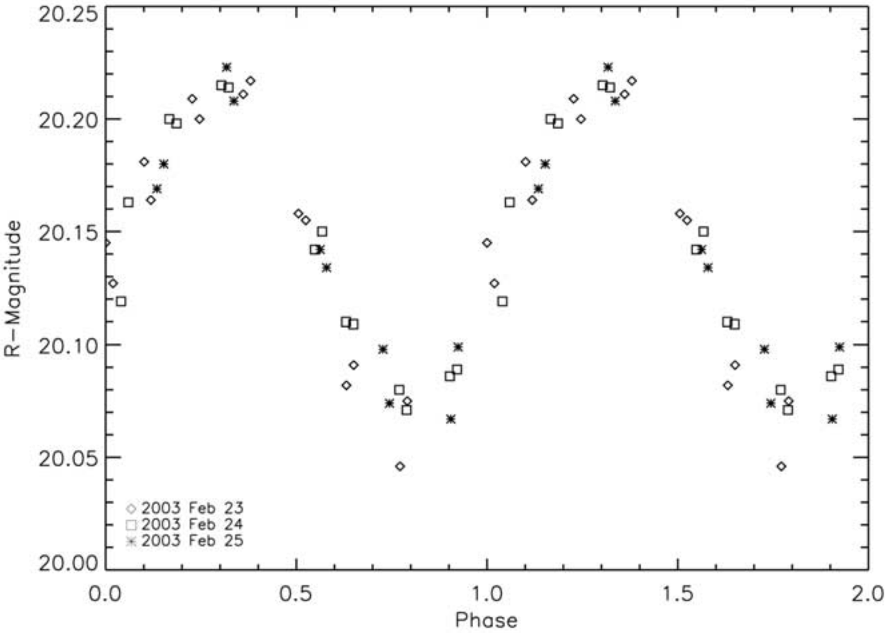

Figure 2. Phased R-band data from the UT February 2003 observations for 2003 AZ_{84}. The period has been phased to the single-peaked period of 6.72 hours. Uncertainties for individual points are ± 0.03 mag.

from these new results will soon be published along with further observations in Sheppard and Jewitt (2004).

2.1. 2003 AZ_{84}

PDM analysis shows that 2003 AZ_{84} has a single-peaked lightcurve period of $P = 6.72 \pm 0.05$ hours (Figure 1). One minimum and one maximum in brightness within a single night were observed and put the full single-peaked lightcurve just over 6 hours, in agreement with the PDM analysis. We phased the data and found the 6.72 hour period to be very good (Figure 2). The peak-to-peak variation is $\Delta m = 0.14 \pm 0.03$ magnitudes. We possess no evidence to show whether the lightcurve is singly periodic (as expected from surface albedo variations) or doubly periodic (consistent with aspherical shape).

2.2. (24835) 1995 SM_{55}

We observed (24835) 1995 SM_{55} for five nights in October 2001. The KBO was found to have very scattered photometry for its brightness (error bars on the photometry are only 0.03 magnitudes), and a good periodic lightcurve could not be identified. We thus reported this object as having a flat lightcurve in our secondary sample in Sheppard and Jewitt (2002). Further observations were obtained in

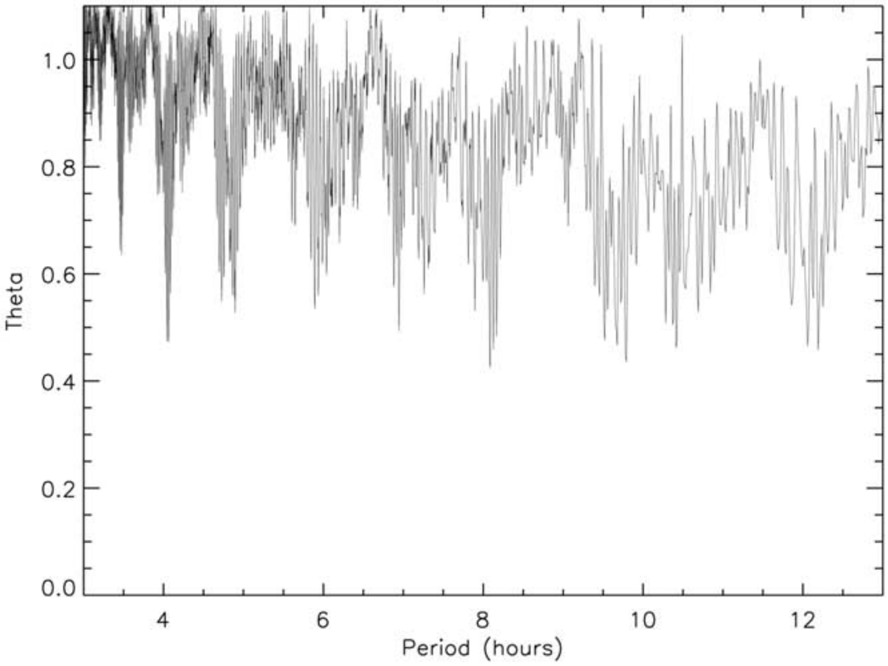

Figure 3. The PDM plot for 1995 SM_{55}. Best fits from this plot are the 4.04 hour single-peaked fit and the 8.08 hour double-peaked fit. Both are flanked by aliases.

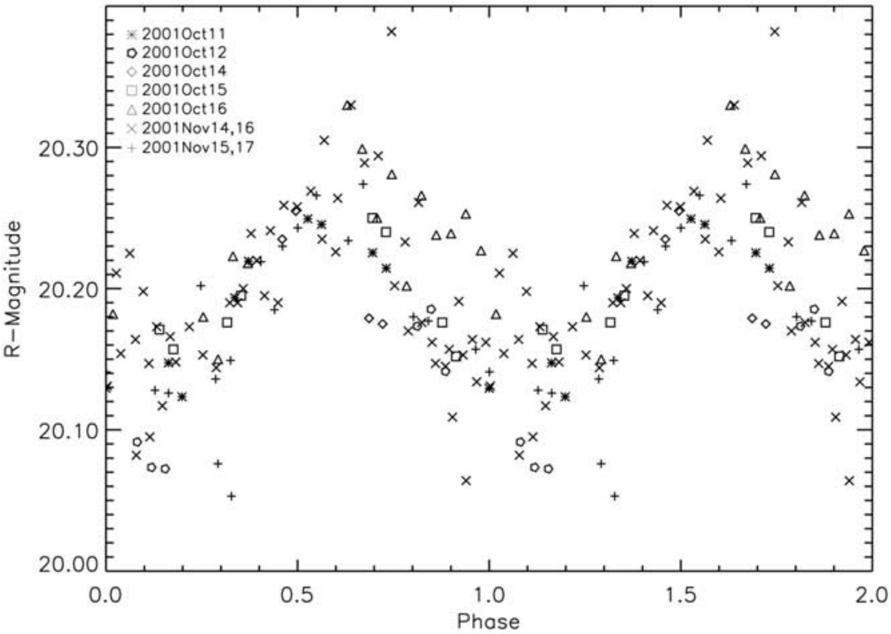

Figure 4. Single-peaked 4.04 hour phased R-band data from the UT October and November 2001 observations for 1995 SM_{55}. Uncertainties for individual points are ± 0.03 mag.

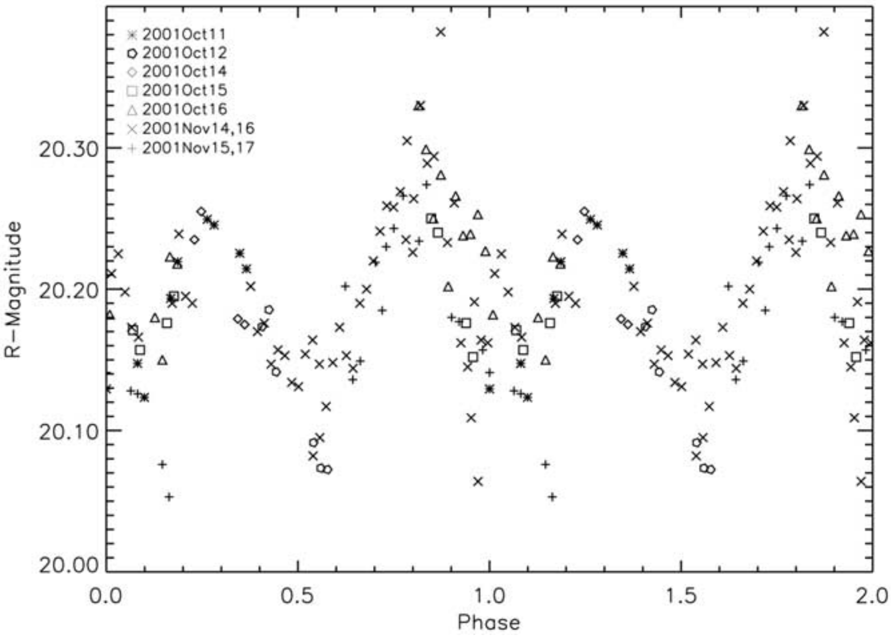

Figure 5. Double-peaked 8.08 hour phased R-band data from the UT October and November 2001 observations for 1995 SM_{55}. Uncertainties for individual points are ± 0.03 mag.

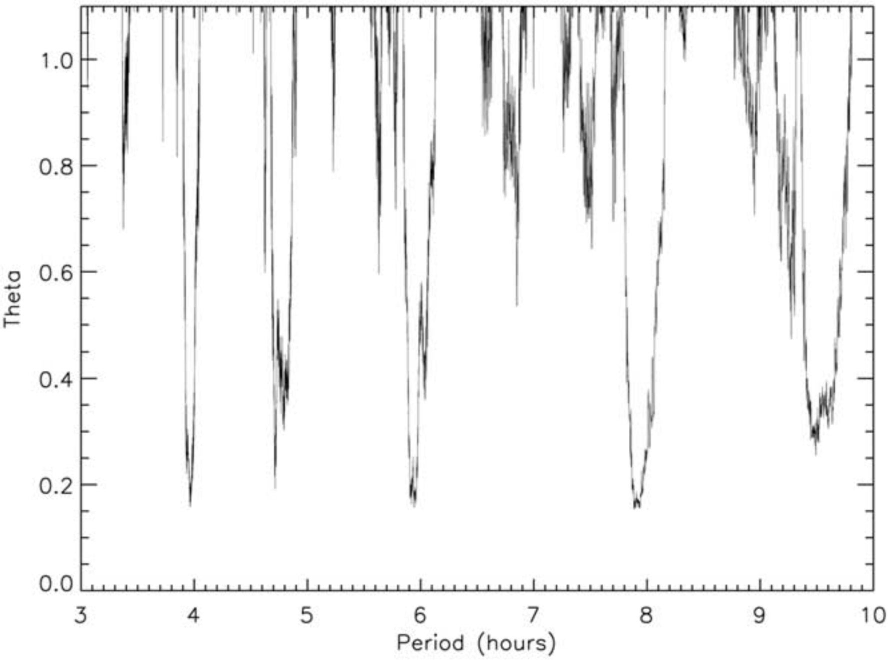

Figure 6. The PDM plot for 1996 TO_{66} from our UT October 2001 data. Best fits from this plot are the 3.96 hour single-peaked fit and the 7.92 hour double-peaked fit.

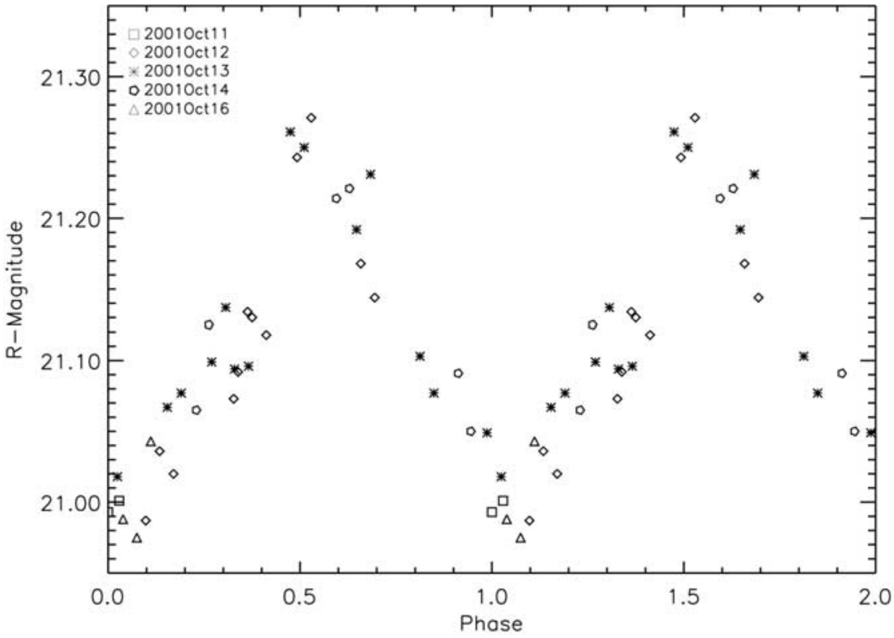

Figure 7. Single-peaked 3.96 hour phased R-band data from the UT October 2001 observations for 1996 TO_{66}. Uncertainties for individual points are ± 0.03 mag.

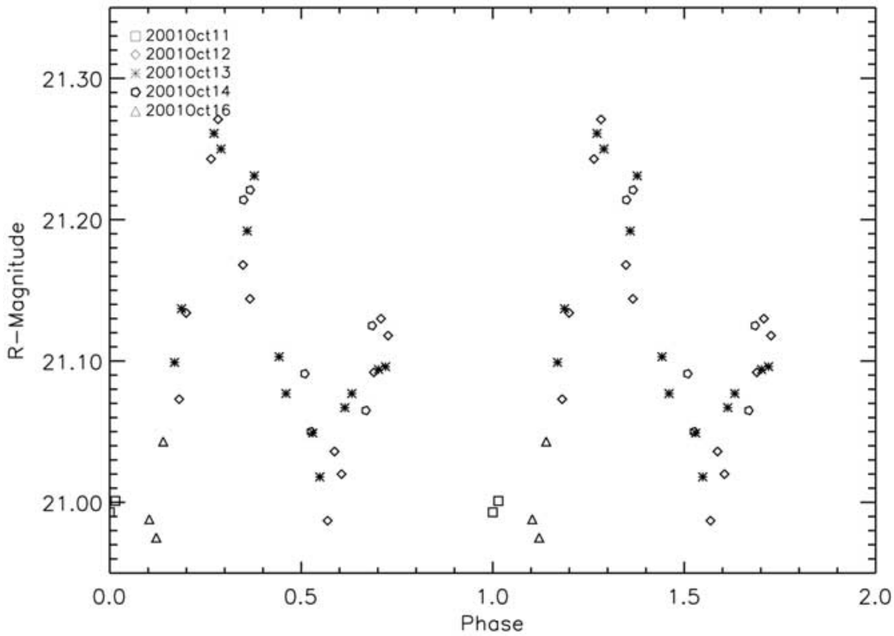

Figure 8. Double-peaked 7.92 hour phased R-band data from the UT October 2001 observations for 1996 TO_{66}. Uncertainties for individual points are ± 0.03 mag.

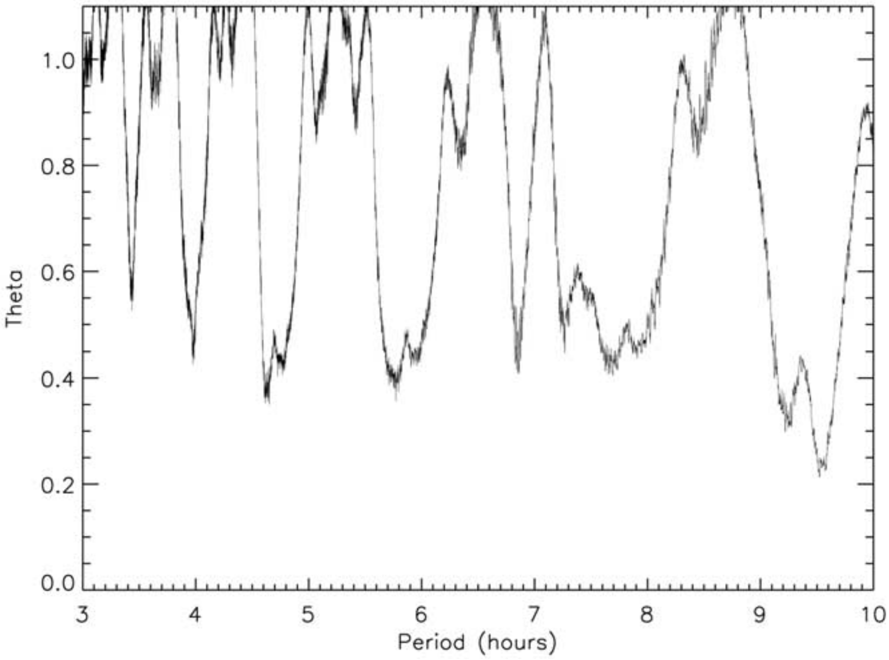

Figure 9. The PDM plot for 1996 TO_{66} using the observations in 1998 taken by Hainaut et al. (2000). This PDM plot looks very similar to our 2001 observations PDM plot with good 3.96 hour single-peaked and 7.92 hour double-peaked fits.

November 2001 to determine if the scattered photometry was caused by noise. With the additional photometry we were able to find a rotational lightcurve with single-peaked period near $P = 4$ hours (Figure 3). Phasing the data together again showed that the single-peaked lightcurve was extremely noisy given our uncertainties (Figure 4). Phasing the data to a possible double-peaked lightcurve of 8 hours is also very noisy (Figure 5). An average peak-to-peak lightcurve amplitude is 0.19 ± 0.05. It appears that the amplitude of the rotational lightcurve may be variable from night to night.

Trujillo and Brown (2003) observed 1995 SM_{55} with the Hubble Space Telescope and found no evidence that it is a binary object. However, their constraint applies only to satellites with separation ≥ 0.1 arcseconds and having a magnitude difference ≤ 2.5. Therefore it remains possible that the "noisy" lightcurve of 1995 SM_{55} is due to the presence of multiple periods in the photometric data caused by an unresolved companion. Only protracted, highly accurate photometric series can show whether or not this is the case. It is interesting that 1995 SM_{55} is one of the bluest KBOs known (V-R = 0.38; see Hainaut and Delsanti (2002)). It may be that blue objects have recently had their volatile-rich insides exposed, possibly by a collision. Thus the amplitude variation seen for 1995 SM_{55} may be affected by cometary activity from freshly exposed material. The large scatter in photometry

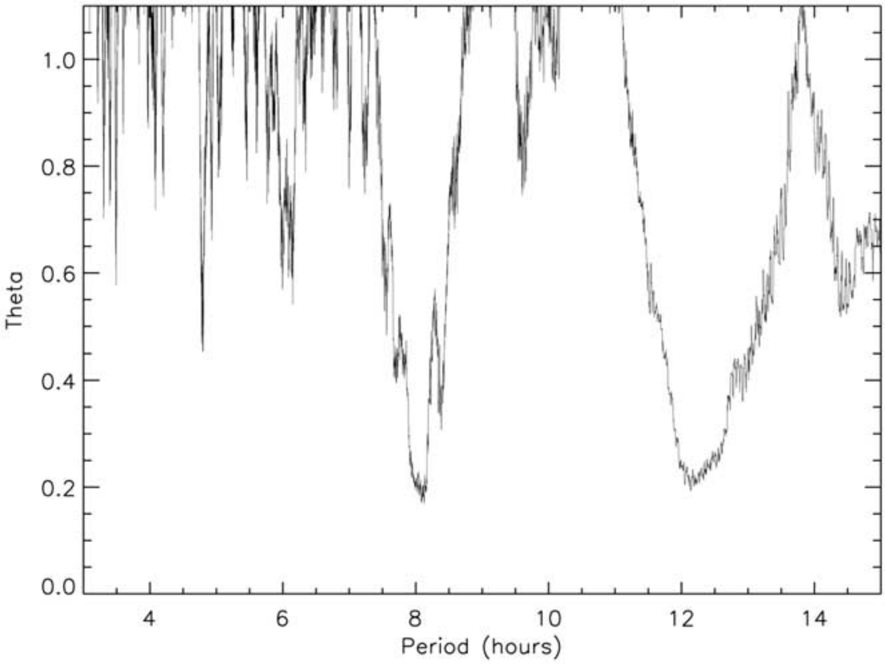

Figure 10. The phase dispersion minimization (PDM) plot for 2002 TX_{300}. Best fits from this plot are the 8.12 and 12.10 hour single-peaked fits.

could also be due to the object being in a complex rotational state, although it is difficult to see how such a state could be maintained other than by forced precession due to a satellite or a very unlikely recent collision since the damping time for wobbles is short (Burns and Safronov, 1973). Further observations of 1995 SM_{55} are needed to understand its peculiar lightcurve nature.

2.3. (19308) 1996 TO_{66}

A similar situation has been invoked for the very blue object (19308) 1996 TO_{66} in which the lightcurve was reported to show signs of variability (Hainaut et al. 2000; Sekiguchi et al. 2002). We observed 1996 TO_{66} in November 2001 and PDM analysis of our data shows possible rotational single-peaked lightcurves at about 3.96 ± 0.04 and 4.80 ± 0.05 hours and double-peaked periods around 5.90 ± 0.05, 7.92 ± 0.04 and 9.6 ± 0.1 hours (Figure 6). When phasing the data to these values, all seem plausible, but the single-peaked period near 3.96 hours and the corresponding double-peaked period near 7.92 hours are significantly better (Figures 7 and 8). We find the peak-to-peak amplitude of 1996 TO_{66} to be 0.26 ± 0.03 magnitudes in our 2001 observations.

Hainaut et al. (2000) reported a 6.25 hour period for 1996 TO_{66} in data taken in 1997 (0.12 magnitudes in amplitude) and 1998 (0.33 magnitudes) and later

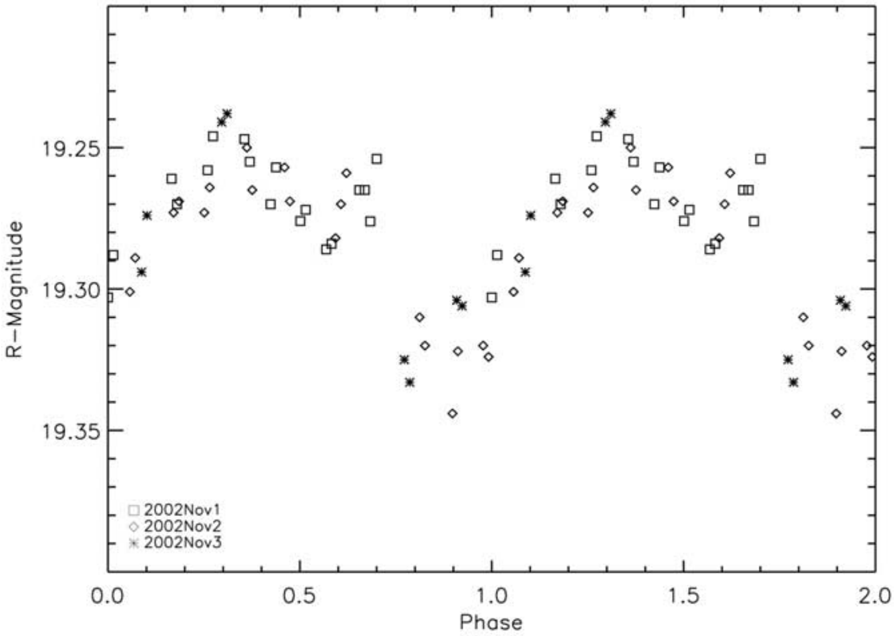

Figure 11. Phased R-band data from the UT November 2002 observations for 2002 TX_{300}. The period has been phased to the single-peaked period of 8.12 hours. Uncertainties for individual points are ± 0.02.

affirmed this period in photometry from 1999 (0.21 magnitudes; Sekiguchi et al. (2002)). They suggest that changes in the lightcurve period from double-peaked to single-peaked as well as in the amplitude between 1997 and 1998 can be attributed to activity, possibly outgassing, in 1996 TO_{66}. Phasing our 2001 data to 6.25 hours gives an implausible lightcurve. We found that the very sparsely sampled Sekiguchi et al. (2002) data from 1999 observations of 1996 TO_{66} are consistent with many periods, including the periods found in our 2001 data. O. Hainaut kindly provided us with the photometric measurements for the 1997 and 1998 observations of 1996 TO_{66} described in Hainaut et al. (2000); the data currently can also be found on the Small Bodies Node of the Planetary Data System at http://www.psi.edu/pds/tnolc.html. In examining this data we could not find a significant lightcurve in the 1997 data ($\leq$ 0.1 magnitudes in amplitude). In our PDM analysis of the Hainaut el al. data from 1998 we found similar periods for 1996 TO_{66} as in our 2001 observations (Figure 9). We do not find strong evidence for the 6.25 hour period in the Hainaut et al. data from 1998.

We do not see any evidence that the period of 1996 TO66 has changed between the 1997, 1998, 1999 and 2001 observations. Romanishin and Tegler (1999) found the lightcurve for 1996 TO_{66} in 1997 to be $\leq$ 0.1 magnitudes, seemingly corroborating the small amplitude reported by Hainaut et al. Thus, while there is no

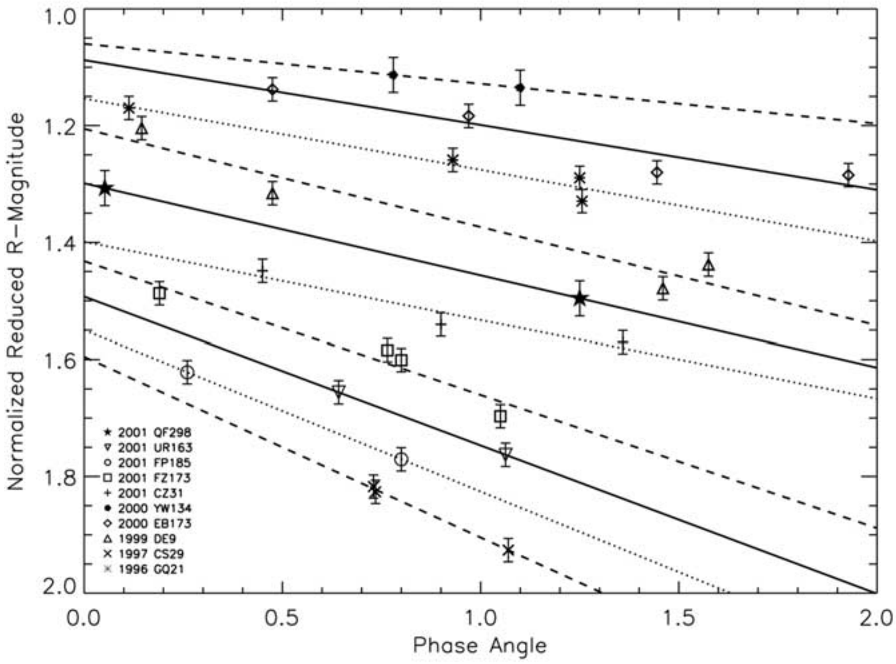

Figure 12. Phase functions for the new observations of KBOs observed at several phase angles. The KBO phase functions appear linear to first order. Reduced magnitudes have been normalized and offset in order to display the phase functions efficiently.

evidence for a change in rotation period, the lightcurve amplitude of 1996 TO$_{66}$ may have changed since 1997.

2.4. (55636) 2002 TX$_{300}$

PDM analysis shows that (55636) 2002 TX$_{300}$ has a single-peaked lightcurve period of either $P = 8.12 \pm 0.08$ or $P = 12.101 \pm 0.08$ hours (Figure 10). Both single-peaked periods appear acceptable in the phased data (Figure 11) with a peak-to-peak variation of $\Delta m = 0.08 \pm 0.02$ magnitudes.

2.5. FLAT ROTATIONAL LIGHTCURVE OBJECTS

Ten KBOs ((55637) 2002 UX$_{25}$, (55638) 2002 VE$_{95}$, (47171) 1999 TC$_{36}$, (42355) 2002 CR$_{46}$, (28978) Ixion 2001 KX$_{76}$, 2000 YW$_{134}$, (42301) 2001 UR$_{163}$, 2001 QF$_{298}$, 2001 FP$_{185}$, and 2001 KD$_{77}$) showed no measurable photometric variations (Table I), by which we mean that their lightcurves have range ≤ 0.1 magnitudes and/or period > 24 hours. A few objects show hints of variability that might, with more data, emerge as rotationally modulated lightcurves. The KBO 2001 YW$_{134}$ has a variation of about 0.1 magnitudes near a 5 hour single-peaked period on one night, but the object appears mostly flat on the second night over 5 hours. Finally,

TABLE I
Properties of newly observed KBOs

Name		m_R[a]	Nights[b]	Δm_R[c]	Single[d]	Double[e]
		(mag)	(#)	(mag)	(hrs)	(hrs)
(55636)	2002 TX_{300}	19.29 ± 0.04	3	0.08 ± 0.02	8.12 ± 0.08	16.24 ± 0.08
					12.10 ± 0.08	24.20 ± 0.08
(55637)	2002 UX_{25}	19.65 ± 0.02	2	<0.06	–	–
(55638)	2002 VE_{95}	19.68 ± 0.02	1	<0.06	–	–
(47171)	1999 TC_{36}	19.80 ± 0.02	2	<0.05	–	–
(42355)	2002 CR_{46}	19.82 ± 0.02	4	<0.05	–	–
(28978) Ixion	2001 KX_{76}[f]	19.84 ± 0.02	3	<0.05	–	–
	2003 AZ_{84}	20.14 ± 0.07	3	0.14 ± 0.03	6.72 ± 0.05	13.44 ± 0.05
(24835)	1995 SM_{55}[f]	20.20 ± 0.10	9	0.19 ± 0.05	4.04 ± 0.03	8.08 ± 0.03
	2000 YW_{134}	20.67 ± 0.05	2	<0.1	?	?
(42301)	2001 UR_{163}	20.86 ± 0.03	3	<0.08	–	–
(19308)	1996 TO_{66}[f]	21.12 ± 0.13	5	0.26 ± 0.03	3.96 ± 0.04	7.92 ± 0.04
	2001 FP_{185}	21.15 ± 0.03	4	<0.06	–	–
	2001 QF_{298}	21.41 ± 0.06	4	<0.12	?	?
	2001 KD_{77}	21.48 ± 0.03	3	<0.07	–	–

[a] Mean R-band magnitude on the date having the majority of observations.

[b] Number of nights used to determine the lightcurve.

[c] The peak to peak range of the lightcurve.

[d] The lightcurve period if there is one maximum per period.

[e] The lightcurve period if there is two maxima per period.

[f] Initial details were given in our secondary sample in Sheppard and Jewitt (2002). Additional observations have been obtained and thus we give further details on the objects here.

the faint KBO 2001 QF_{298} appears to have variations of about 0.1 magnitudes. Confirmation of these subtle lightcurves will require more data, with a larger telescope most likely required.

3. Phase Angle Results

We add additional measurements for four KBO phase functions reported in Sheppard and Jewitt (2002) as well as six new KBOs (Table II). We continue to find that the slopes are very steep and the additional points show that the phase functions are linear to first order between phase angles of 0 and 2 degrees (Figure 12). For the phase functions we use the notation $\phi(\alpha) = 10^{-0.4\beta\alpha}$, where α is the phase angle in degrees and β is the "linear" phase coefficient. The median phase coefficient using all 13 KBOs observed at significantly different phase angles from Sheppard and Jewitt (2002) and this work is $\beta = 0.16 \pm 0.01$ magnitudes per degree. Though not

TABLE II

New phase function data for KBOs

Name		H	G	$\beta(\alpha < 2^\circ)$[a]	N[b]
(42301)	2001 UR163	3.75 ± 0.05	−1.00 ± 0.30	0.25 ± 0.05	2
	2000 YW134	4.29 ± 0.20	+ 0.57 ± 0.50	0.07 ± 0.12	2
(38628)	Huya 2000 EB173	4.45 ± 0.01	+ 0.10 ± 0.03	0.11 ± 0.01	4
(26181)	1996 GQ21	4.47 ± 0.01	+0.12 ± 0.03	0.12 ± 0.02	4
(26375)	1999 DE9	4.55 ± 0.02	−0.34 ± 0.05	0.17 ± 0.05	4
(26375)	1997 CS29	4.78 ± 0.10	−1.42 ± 0.30	0.31 ± 0.10	3
	2001 QF298	4.95 ± 0.10	−0.19 ± 0.10	0.16 ± 0.03	2
	2001 CZ31	5.54 ± 0.02	−0.03 ± 0.05	0.13 ± 0.03	3
	2001 FZ173	5.63 ± 0.03	−0.77 ± 0.08	0.23 ± 0.03	4
	2001 FP18S	5.79 ± 0.05	−1.13 ± 0.20	0.28 ± 0.05	2

[a] $\beta(\alpha < 2^\circ)$ is the phase coefficient at phase angles $< 2^\circ$.

[b] N is the number of different observing runs used and thus the number of points plotted. Most objects were observed on many consecutive nights during each of several observing runs. These data were all averaged together to obtain points with very small uncertainties.

necessarily useful at the low phase angles for which KBOs can be observed, we also include the H and G formalism as described in Bowell et al. (1989) in Table II in order to fully compare our results with other works. As previously, we note that the large, high albedo object Pluto has a much lower phase function than the smaller KBOs (0.0294 ± 0.0011 mag/deg; Buie et al. (1997)). The intermediate albedo/sized Charon has an intermediate phase function (0.0866 ± 0.0078 mag/deg; Buie et al. (1997)). Although there exists no unique correlation between albedo and phase function at low phase angles, our data are consistent with low albedos for the 100–1000 km scale KBOs.

Acknowledgements

This work was supported by a grant to D.J. from the NASA Origins Program.

References

Bowell, E. et al. (1989, ‘Application of Photometric Models to Asteroids’, in R. Binzel, T. Gehrels and M. Matthews (eds.), *Asteroids II*, Tucson, Arizona.

Buie, M., Tholen, D., and Wasserman, L.: 1997, ‘Separate Lightcurves of Pluto and Charon’, *Icarus* **125**, 233–244.

Burns, J. and Safronov, V.: 1973, ‘Asteroid Nutation Angles’, *MNRAS* **165**, 403–411.

Farinella, P. and Davis, D.: 1996, ‘Short-Period Comets: Primordial Bodies or Collisional Fragments?’, *Science* **273**, 938–941.

Hainaut, O. et al.: 2000, ‘Physical Properties of TNO 1996 TO66, Lightcurves and Possible Cometary Activity’, *A&A* **356**, 1076–1088.

Hainaut, O. and Delsanti, A.: 2002, ‘Colors of Minor Bodies in the Outer Solar System: A statistical Analysis’, *A&A* **389**, 641–664.

Jewitt, D. and Sheppard, S.: 2002, ‘Physical Properties of Trans-Neptunian Object (20000) Varuna’, *Astron. J.* **123**, 2110–2120.

Romanishin, W. and Tegler, S.: 1999, ‘Rotation Rates of Kuiper-Belt Objects from Their Light Curves’, *Nature* **398**, 129–132.

Sekiguchi, T., Boehnhardt, H., Hainaut, O., and Delahodde, C.: 2002, ‘Bicolour Lightcurve of TNO 1996 T066 with the ESO-VLT’, *A&A* **385**, 281–288.

Sheppard, S. and Jewitt, D.: 2002, ‘Time-Resolved Photometry of Kuiper Belt Objects: Rotations, Shapes, and Phase Functions’, *Astron. J.* **124**, 1757–1775.

Sheppard, S. and Jewitt, D.: 2004, in preparation.

Stellingwerf, R.: 1978, ‘Period Determination Using Phase Dispersion Minimization’, *Astron. J.* **224**, 953–960.

Trujillo, C. and Brown, M.: 2003, ‘A Search for Bright Kuiper Belt Binaries with the Hubble Space Telescope’, *Astron. J.* submitted.