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Photometric observations of nine Transneptunian objects and Centaurs

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ABSTRACT

We present the results of photometric observations of six Transneptunian objects and three Centaurs, estimations of their rotational periods and corresponding amplitudes. For six of them we present also lower limits of density values. All observations were made using 3.6-m TNG telescope (La Palma, Spain). For four objects – (148975) 2001 XA255, (281371) 2008 FC76, (315898) 2008 QD4, and 2008 CT190 – the estimation of short-term variability was made for the first time. We confirm rotation period values for two objects: (55636) 2002 TX300 and (202421) 2005 UQ513, and improve the precision of previously reported rotational period values for other three – (120178) 2003 OP32, (145452) 2005 RN43, (444030) 2004 NT33 – by using both our and literature data. We also discuss here that small distant bodies, similar to asteroids in the Main belt, tend to have double-peaked rotational periods caused by the elongated shape rather than surface albedo variations.

Key words: techniques: photometric – Kuiper belt: general.

1 INTRODUCTION

The study of short-term photometric variability of small Solar system bodies let us to estimate such important physical characteristics as rotation period, shape, and surface heterogeneity. It is believed that rotational rates and shapes of minor Solar system objects might be a function of their sizes and densities (Sheppard, Lacerda & Ortiz 2008). The rotational properties of the smallest objects are thought to be significantly altered since the formation, while the mid-sized objects are considered to be affected only by quite recent collisional events, and, finally, the largest among minor bodies population have their momentum values preserved in the most pristine condition (Farinella & Davis 1996; Davis & Farinella 1997; Morbidelli & Brown 2004; Sheppard et al. 2008).

Up to date, more than 2500 Transneptunian objects (TNOs) and Centaurs are discovered; however, the rotational variability has been measured for less than 100 objects (Harris, Warner & Pravec 2016). We note that only for about 10 of them the rotation period was determined precisely (code 3 in the A. Harris data base). Moreover, in most cases two possible values of rotational period are given because of no confident distinction between single and double-peaked light curves. Such situation can be explained by faintness of these distant objects, and, as a result, inability for obtaining accurate photometry with small telescopes. The use of moderate and large telescopes for the purpose of rotation period determination is usually very limited in time. But to measure a confident rotational period the object should be observed during at least 2–3 successive nights.

In this paper we present new photometric observations of a selected sample of nine outer Solar system objects, six TNOs and three Centaurs. Rotational variability of four of these objects was observed for the first time. We describe observational circumstances and data reduction technique and present our results and their analysis together with the literature data when they are available.

2 OBSERVATIONS AND DATA REDUCTION

Photometric observations were carried out during two observational runs in 2009 March and August at a 3.6-m TNG telescope (La Palma, Spain). We used the DOLORES (Device Optimized for the LOw RESolution) instrument equipped with a E2V 4240 × 2048 pixel thinned back-illuminated, deep-depleted, Astro-BB-coated CCD with a pixel size of 13.5 μm. All photometric measurements were taken in the broad-band *R* filter.

Data reduction was made following the standard procedure, which included bias subtraction from the raw data and flat-field correction, using MIDAS software package. We performed only differential photometry. To minimize random errors only bright field stars (typically three of them per image) were used. The accuracy of photometry measurements is about 0.02–0.03 mag.

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Table 1. Observational circumstances.

Object	Date UT	r (au)	Δ (au)	α (deg)
(55636) 2002 TX300	2009 Aug 25.05	41.518	40.898	1.11
	2009 Aug 26.09	41.518	40.886	1.10
(120178) 2003 OP32	2009 Aug 22.02	41.454	40.484	0.40
	2009 Aug 24.00	41.455	40.486	0.40
(145452) 2005 RN43	2009 Aug 21.92	40.695	39.706	0.30
	2009 Aug 22.96	40.695	39.705	0.29
	2009 Aug 24.00	40.695	39.705	0.29
(148975) 2001 XA255	2009 Mar 29.06	9.566	8.616	1.93
(202421) 2005 UQ513	2009 Aug 22.04	48.741	48.104	0.93
	2009 Aug 23.06	48.740	48.093	0.92
	2009 Aug 24.06	48.740	48.081	0.91
(281371) 2008 FC76	2009 Aug 25.03	11.270	10.381	2.55
	2009 Aug 25.98	11.270	10.381	2.55
(315898) 2008 QD4	2009 Mar 26.10	5.878	6.842	2.34
(444030) 2004 NT33	2009 Aug 24.00	38.172	37.325	0.84
	2009 Aug 25.04	38.173	37.329	0.84
2008 CT190	2009 Mar 28.96	34.726	34.146	1.35

In Table 1 we present observational circumstances which include the mean UT, heliocentric (r) and geocentric (Δ) distances, and solar phase angle (α).

3 RESULTS

We observed nine objects, including five classical TNOs (two of them are members of the Haumea family), three Centaurs and one Scattered-disc object (SDO), according to dynamical classification by Gladman, Marsden & Vanlaerhoven (2008). Short-term variabilities of SDO 2008 CT190, Centaurs (148975) 2001 XA255, (281371) 2008 FC76, and (315898) 2008 QD4 were observed for the first time. The rotational periods of the objects that were observed for more than one night were calculated based on Fourier analysis technique (cf. Harris & Lupishko 1989; Magnusson & Lagerkvist 1990). Fig. 1 presents single-night observations, except for 2001 XA255, 2008 QD4, and 2008 CT190 light curves that are shown separately.

Since each object was observed during only one opposition in order to improve the accuracy of rotational period values, we also used literature data (from Thirouin et al. 2010, 2012; Benecchi & Sheppard 2013) in the analysis.

We summarize in Table 2 previously published data on rotation periods and light-curve amplitudes and our new determinations. We also give in Table 2 the orbital type of these objects, and the estimations of diameters and albedos with the corresponding references.

Lower limits of densities were also derived for six objects. We used the tables from Chandrasekhar (1987) for rotationally stable Jacobi ellipsoids, and considered the lower limits of the axial ratio a/b. For simplicity and given the icy-rich nature of TNOs, a fluid body (i.e. a body with no tensile and pressure-dependent strength) assumption is normally used when calculating the densities. We note however, that for 2008 FC76 and 2003 OP32 this approach may not be correct, as their sizes could be too small to acquire the hydrostatic equilibrium. For more details on the calculation of the obtained density limit values we refer the reader to the paper Perna et al. (2009). In Table 3 we provide the lower limits of the axial ratio and estimations of the densities (assuming an elongated shape of the objects and thus the longer period with double extrema light curve).

A caveat is in order at this point. The assumption of hydrostatic equilibrium (inherent in our modelling) is plausible but clearly not 'optimal' for the bodies under consideration. Objects in the TNO-Centaur population tend to be either small enough that non-hydrostatic deviations can explain the light-curve amplitude (as mentioned above), or large enough that albedo variegation (e.g. Pluto) can provide an explanation for the light-curve amplitude.

As can be seen from Table 3 the density lower limits are extremely low and therefore are not giving very significant information, apart from the, non-negligible, fact that none of the observed spins and light-curve amplitudes suggest an unexpected density.

3.1 (55636) 2002 TX300

(55636) 2002 TX300 is a classical TNO, which is one of the largest member of the Haumea family. The object has highly inclined orbit similar to that of (136108) Haumea. Previously reported values of its rotational period vary between 8.12 and 24.2 h (considering both single- and double-peaked light curves) with estimated amplitude of about 0.04–0.09 mag (Sheppard & Jewitt 2003; Ortiz et al. 2004; Thirouin et al. 2010, 2012).

(55636) 2002 TX300 was observed for two consequent nights on 2009 August 24–25. We found the rotational periods 8.04 ± 0.04 h and its double value 16.08 ± 0.04 h with the amplitude of 0.05 ± 0.01 mag. The composite light curves for single- and double-peaked rotational periods are shown in Figs 2 and 3, respectively.

3.2 (120178) 2003 OP32

(120178) 2003 OP32 is another member of the Haumea collisional family that we observed. It also has orbital parameters similar to that of Haumea. This object was previously observed by different authors that report rotational periods from 4.05 to 9.71 h (Rabinowitz et al. 2008; Thirouin et al. 2010; Benecchi & Sheppard 2013; Thirouin et al. 2016) and amplitude from 0.13 to 0.20 mag. The authors of above-mentioned papers did not report a light-curve asymmetry, and could not give a preference to single- or double-peaked variability rate.

We observed this object for two nights on 2009 August 21 and 23. Our results show a difference in amplitude of about 0.03 mag between two peaks, suggesting double-peaked period. We used previously published data to both check our assumption on asymmetry and improve the precision of the rotational period. The composite light curve using all available to us literature data is shown in Fig. 4. The rotation period is 9.7057 ± 0.0001 h with the primary amplitude 0.18 ± 0.01 mag and secondary 0.15 ± 0.01 mag.

3.3 (145452) 2005 RN43

(145452) 2005 RN43 is a classical Kuiper belt object on a moderately inclined and almost circular orbit. It was observed previously by Thirouin et al. (2010) and Benecchi & Sheppard (2013). They found rotational periods of 5.62 and 6.95 h respectively with quite small light-curve amplitude of about 0.05 mag.

The observations of this TNO were performed during three consequent nights on 2009 August 21–23. From our and published data we found rotational periods of 6.946 ± 0.05 h for a single-peaked light curve (Fig. 5) and 13.892 ± 0.05 h for a double-peaked light curve (Fig. 6). The light-curve amplitude is 0.04 ± 0.01 mag.

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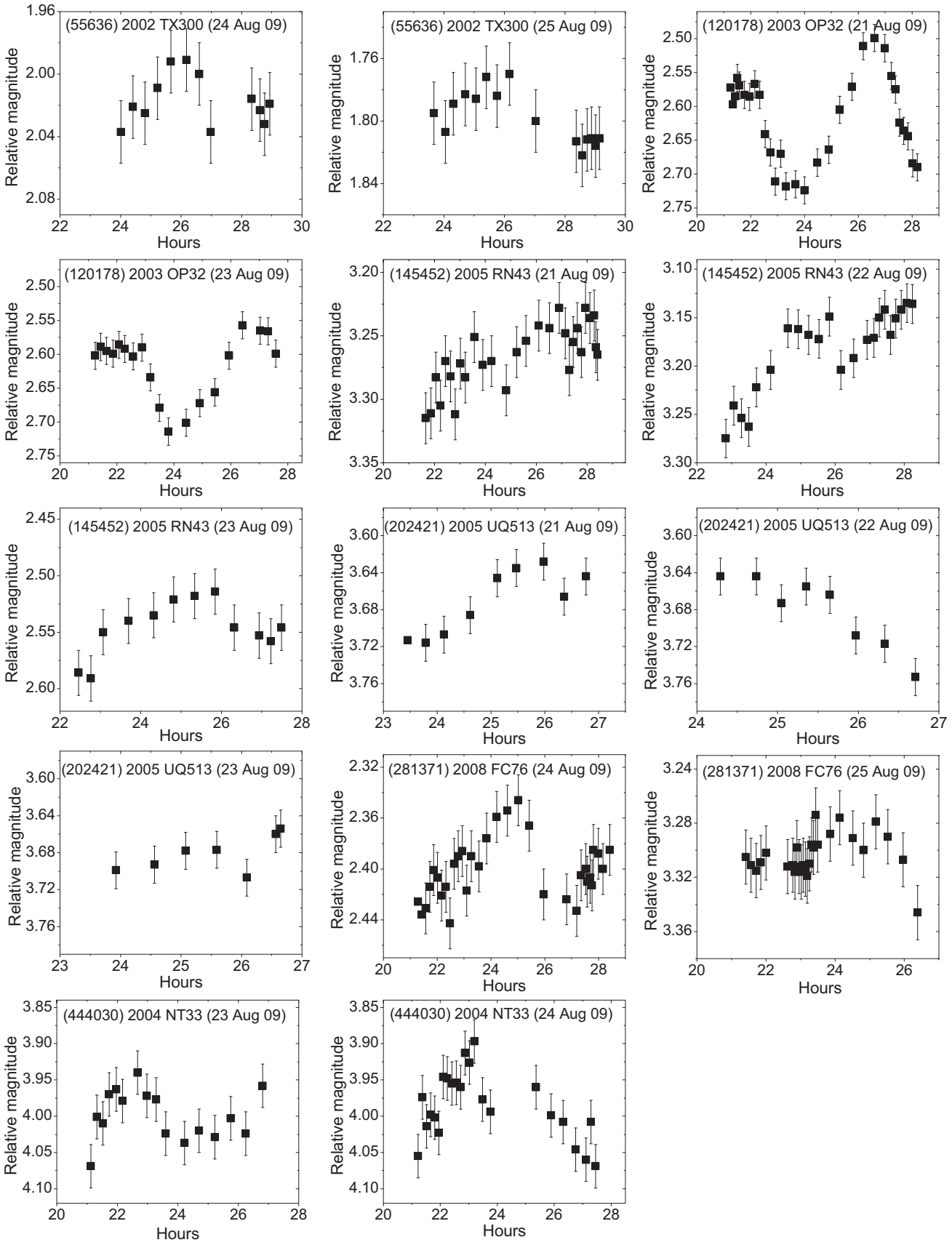

Figure 1. Individual light curves of the objects that were observed for more than one night.

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Table 2. Summary on the observed objects.

Object	Orbital type	H[a](mag)	D (km)	pv	P single (h)	P double (h)	*A* (mag)	Reference
(55636) 2002 TX300	Cl	3.3	286[1]	0.88[1]	8.12 ± 0.08	16.24 ± 0.08	0.02 ± 0.02	Sheppard & Jewitt (2003)
					12.10 ± 0.08	24.20 ± 0.08	0.08 ± 0.02	Sheppard & Jewitt (2003)
					–	15.78 ± 0.05	0.09 ± 0.02	Ortiz et al. (2004)
					8.16 ± 0.05	–	0.04 ± 0.01	Thirouin et al. (2010)
					8.15 ± 0.05	–	0.05 ± 0.01	Thirouin et al. (2012)
					8.04 ± 0.04	16.08 ± 0.04	0.05 ± 0.01	This paper
(120178) 2003 OP32	Cl	4.1	∼216[1]	0.88[1]	4.854 ± 0.003	–	0.20 ± 0.04	Rabinowitz et al. (2008)
					4.05 ± 0.05	–	0.13 ± 0.01	Thirouin et al. (2010)
					4.85	9.71	0.18 ± 0.01	Benecchi & Sheppard (2013)
					4.85		0.14 ± 0.02	Thirouin et al. (2016)
					–	9.7057 ± 0.0001	0.15 ± 0.01; 0.18 ± 0.01	This paper
(145452) 2005 RN43	Cl	3.9	679[2]	0.11[2]	5.62 ± 0.05	–	0.04 ± 0.01	Thirouin et al. (2010)
					6.95 ± 0.05	13.89 ± 0.05	0.06 ± 0.01	Benecchi & Sheppard (2013)
					6.946 ± 0.05	13.892 ± 0.05	0.04 ± 0.01	This paper
(148975) 2001 XA255	Cen	11.1	38[3]	0.04[3]	>7	>14	∼0.2	This paper
(202421) 2005 UQ513	Cl	3.4	498[4]	0.20[4]	7.03 ± 0.05	–	0.06 ± 0.02	Thirouin et al. (2012)
					7.03 ± 0.005	14.06 ± 0.005	0.07 ± 0.01	This paper
(281371) 2008 FC76	Cen	9.3	∼41–82[5]	–	5.93 ± 0.05	11.86 ± 0.05	0.04 ± 0.01	This paper
(315898) 2008 QD4	Cen	11.3	∼16–35[5]	–	>7	>14	∼0.15	This paper
(444030) 2004 NT33	Cl	4.7	423[4]	0.13[4]	57.87 ± 0.05	–	0.04 ± 0.01	Thirouin et al. (2012)
					7.871 ± 0.05	15.742 ± 0.05	0.05 ± 0.01	This paper
2008 CT190	SDO	5.5	∼236–470[5]	–	>5	>10	∼0.15	This paper

[a]From Minor Planet Centre data base,
[1]Elliot et al. (2010), [2]Vilenius et al. (2012), [3]Bauer et al. (2013), [4]Vilenius et al. (2014), [5]Assuming an albedo range of 0.05–0.20.

Table 3. Lower limits of axial ratio and density values (together with diameter and periods, from Table 2). See the text for details.

Object	Axial ratio, *a*/*b*	ρ (g cm^{-3})	Diameter (km)	Period, single/double (h)
(55636)	1.05	0.15	286	8.04/16.08
(120178)	1.18	0.41	∼108	–/9.706
(145452)	1.04	0.20	679	6.95/13.892
(202421)	1.07	0.20	498	7.03/14.06
(281371)	1.04	0.28	∼41–82	5.93/11.86
(444030)	1.05	0.16	423	7.871/15.742

3.4 (148975) 2001 XA255

(148975) 2001 XA255 was first classified as a Centaur, but later de la Fuente Marcos & de la Fuente Marcos (2012) suggested that this object is a dynamically unstable temporary Neptune co-orbital. Authors argue it may be a relatively recent visitor from the scattered disc on its way to the inner Solar system. No rotational period values are reported in the literature. As we observed 2001 XA255 during only one night on 2009 March 28, we can just give a lower limit of a rotational period to be about 7 h (or 14 h if double-peaked) with an amplitude ∼0.2 mag (Fig. 7).

3.5 (202421) 2005 UQ513

(202421) 2005 UQ513 is a classical TNO. Thirouin et al. (2012) reported a rotational variability of 7.03 h and quite small amplitude of 0.06 mag.

From our observations during three nights on 2009 August 21–23 we can confirm this value and suggest 7.03 ± 0.05 h (single-peaked) and 14.06 ± 0.05 h (double-peaked) short-term variability with an amplitude 0.07 ± 0.01 mag. The single- and double-peaked composite light curves for this object are presented in Figs 8 and 9, respectively.

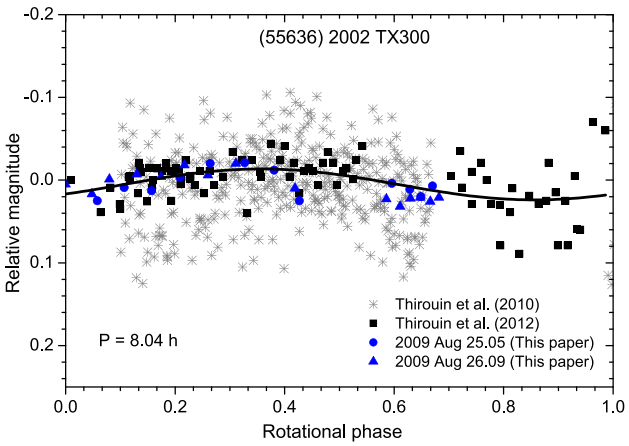

Figure 2. Single-peaked composite light curve of (55636) 2002 TX300. Zero phase is at UT 2009 August 25.7497.

3.6 (281371) 2008 FC76

(281371) 2008 FC76 is a Centaur on a moderately eccentric and highly inclined orbit. No short-term variability values are available in the literature.

We observed this object during two nights on 2009 August 24–25. Our data suggest a rotational period of 5.93 ± 0.05 h (or twice this value 11.86 ± 0.05 h) with peak-to-peak variation of 0.04 ± 0.01 mag. Composite light curves for single- and double-peaked solutions are shown in Figs 10 and 11, respectively.

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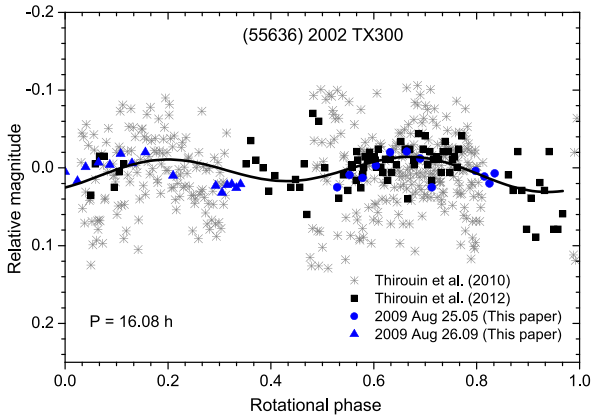

Figure 3. Double-peaked composite light curve of (55636) 2002 TX300. Zero phase is at UT 2009 August 25.7497.

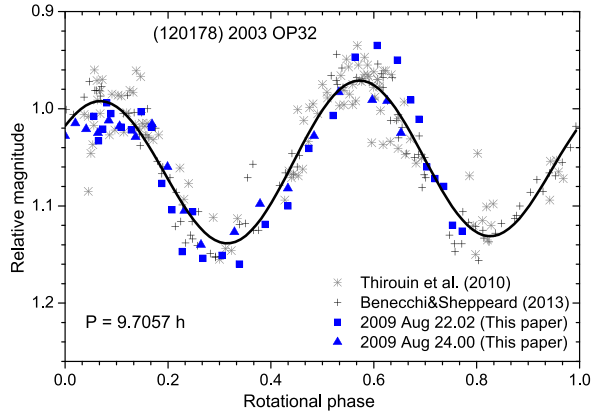

Figure 4. Double-peaked composite light curve of (120178) 2003 OP32. Zero phase is at UT 2009 August 23.6512.

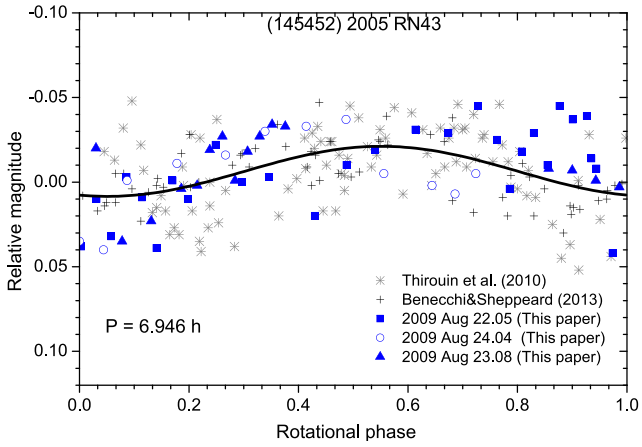

Figure 5. Single-peaked composite light curve of (145452) 2005 RN43. Zero phase is at UT 2009 August 23.7067.

3.7 (315898) 2008 QD4

(315898) 2008 QD4 has been classified as a Centaur on a highly eccentric and highly inclined orbit. No values of its rotational period were reported so far. Based on one-night observations on 2009 March 25 (Fig. 12) we suggest its rotational period to be longer than ∼7 h and light-curve amplitude value of about ∼0.15 mag.

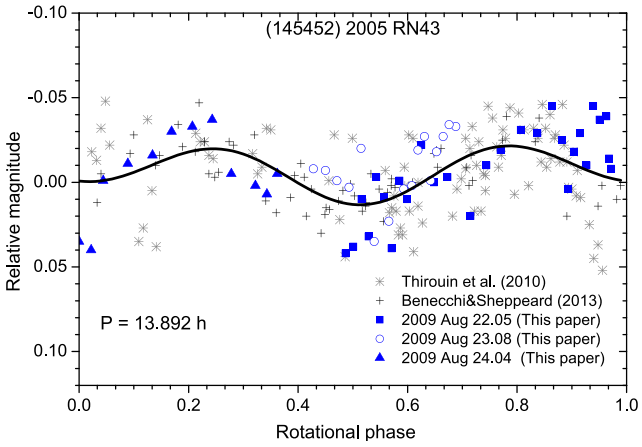

Figure 6. Double-peaked composite light curve of (145452) 2005 RN43. Zero phase is at UT 2009 August 23.7067.

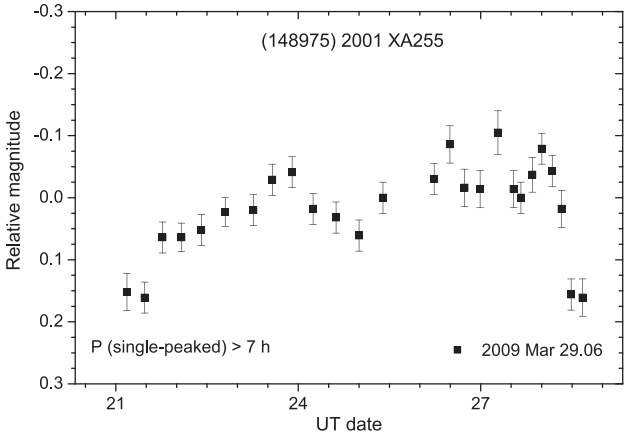

Figure 7. Light curve of (148975) 2001 XA255.

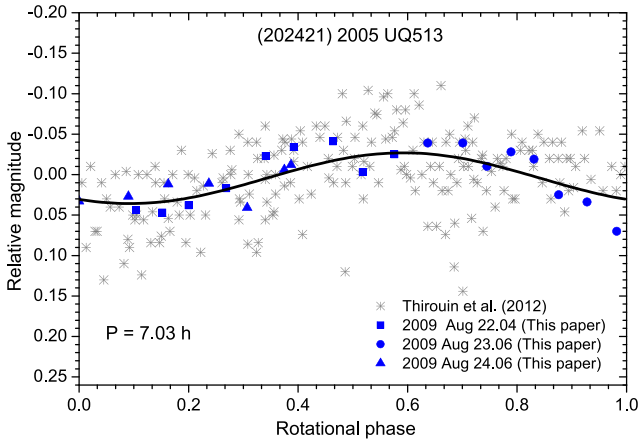

Figure 8. Single-peaked composite light curve of (202421) 2005 UQ513. Zero phase is at UT 2009 August 23.7193.

3.8 (444030) 2004 NT33

(444030) 2004 NT33 is a classical, low-eccentricity, and high-inclination TNO. Previously reported value of its rotation period is 7.87 h (single-peaked light curve), and suggested amplitude is quite low (0.04 mag) (Thirouin et al. 2012). We observed this object on 2009 August 23–24. From our and literature data we found more

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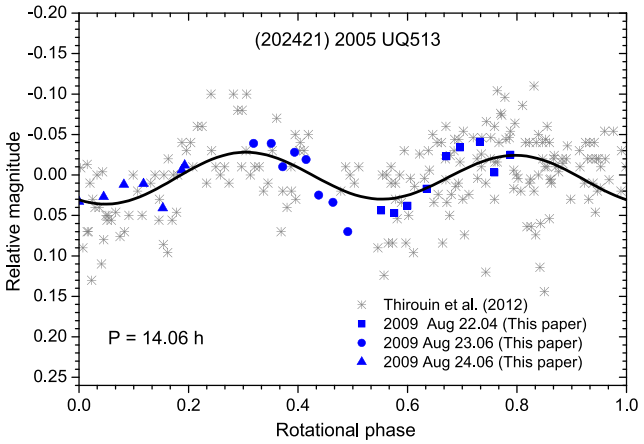

Figure 9. Double-peaked composite light curve of (202421) 2005 UQ513. Zero phase is at UT 2009 August 23.7193.

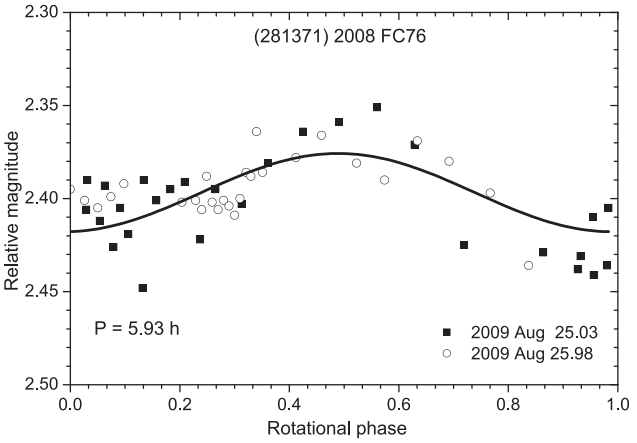

Figure 10. Single-peaked composite light curve of (281371) 2008 FC76. Zero phase is at UT 2009 August 25.8323.

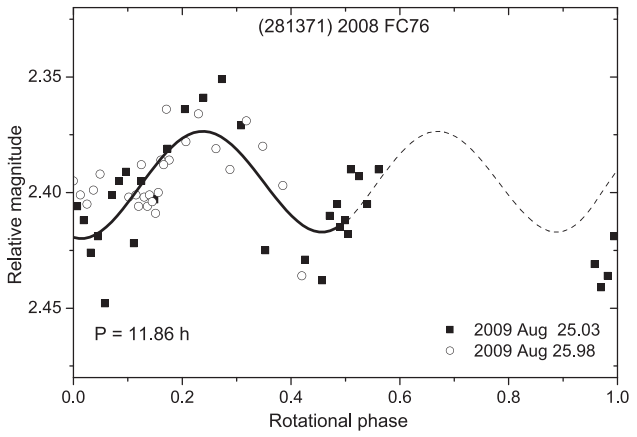

Figure 11. Double-peaked composite light curve of (281371) 2008 FC76. Zero phase is at UT 2009 August 25.8323.

accurate rotational period value of 7.871 ± 0.05 h (15.742 ± 0.05 h for double-peaked period) that is consistent with all of the available data and has an amplitude of 0.05 ± 0.01 mag. Figs 13 and 14 show the composite light curves for single- and double-peaked light curves, respectively.

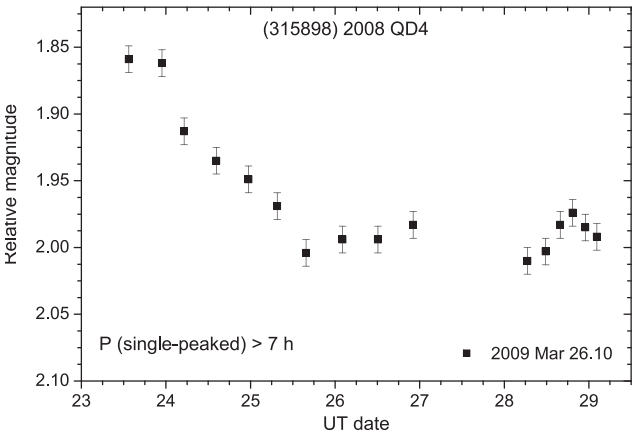

Figure 12. Light curve of (315898) 2008 QD4.

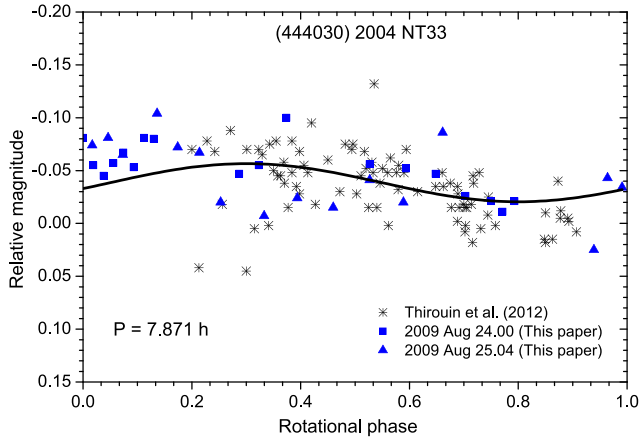

Figure 13. Single-peaked composite light curve of (444030) 2004 NT33. Zero phase is at UT 2009 August 24.6685.

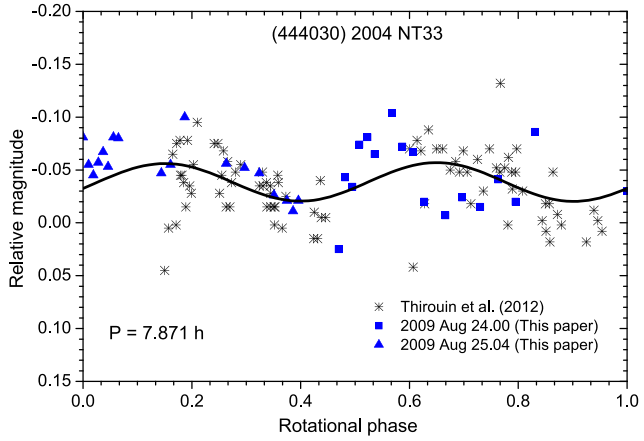

Figure 14. Double-peaked composite light curve of (444030) 2004 NT33. Zero phase is at UT 2009 August 24.6685.

3.9 2008 CT190

2008 CT190 is a high-eccentricity and high-inclination TNO. This object is less studied compared to other objects in our sample. No rotational period was reported previously. From our data obtained only during 4.5 h on 2009 March 28 we suggest a lower limit of

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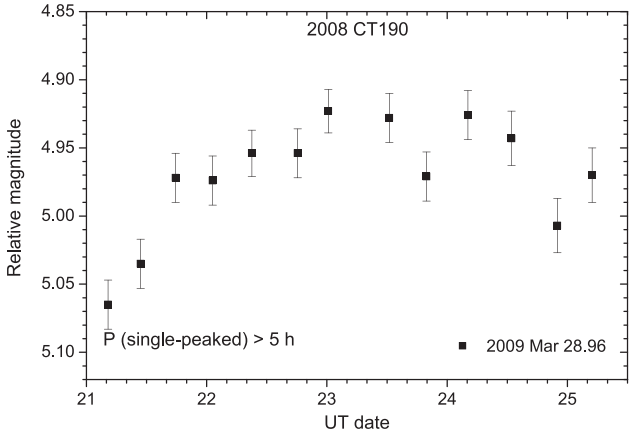

Figure 15. Light curve of 2008 CT190.

rotational period value to be ∼5 h with an amplitude of ∼0.15 mag (Fig. 15).

4 DISCUSSION

The main causes of short-term photometric variability of small Solar system bodies are aspherical shape and surface albedo variations. Light curve with one pair of extrema can be produced only by some kind of surface heterogeneity, whereas light curves with two pairs are usually associated with elongated shape.

It was shown that albedo variation contribution into rotational light curve is relatively small (less than ∼0.2 mag). For bodies with larger amplitudes we postulated an elongated shape with double-peaked rotational periods (see Thirouin et al. 2016, and references therein). As noted before, the underlying assumption based on Jacobi ellipsoids, is at the limits of its applicability in the case of large TNOs and Centaurs and is generally not valid for smaller objects (and asteroids in general), where non-hydrostatic deviations in shape are generally responsible for the light-curve amplitudes.

Indeed, any light-curve asymmetry can be caused by shape and/or albedo irregularities. For the majority of asteroid light curves the primary and secondary peaks differ in amplitude which let us to identify double-peaked periods. In the case of TNOs relatively large rotational periods together with small amplitudes do not let to make a confident distinguish between two peaks. In our sample we found a confident evidence for double-peaked period for only one object.

However, in the case of symmetrical low-amplitude light curves it is more tricky to distinguish between single- and double-peaked periods. Peak-to-peak values gradually decrease and completely disappear while object is approaching pole-on aspect (angle between the rotational axis and the line of sight is 0°). Thus, bodies with low amplitude light curves can be either viewed from near pole-on orientation or have almost spherical shapes (MacLaurin spheroids). Assuming random rotational axis orientation distribution Sheppard & Jewitt (2002) showed that the average viewing angle would be 60°, and near-spherical shapes of low-amplitude bodies are more probable, than polar observing aspect.

It was shown by Sheppard & Jewitt (2002) that a population of outer Solar system objects tend to be statistically more elongated than that in the Main belt. For objects with $D > 200$ km about ∼30 per cent and ∼23 per cent of TNOs have light-curve amplitudes of more than 0.15 and 0.40 mag, respectively, compared to the ∼11 per cent with amplitude more than 0.40 mag for the Main-belt asteroids (Romanishin & Tegler 1999; Sheppard & Jewitt 2002).

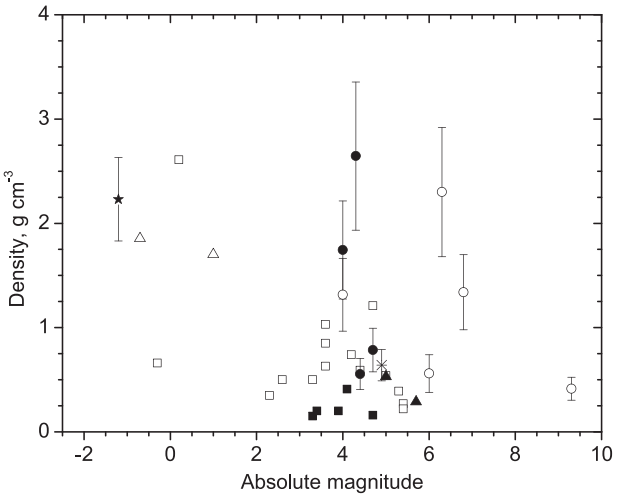

Figure 16. Density estimations of TNOs and Centaurs as a function of their absolute magnitude. Data from this work (filled squares), literature data from Dotto et al. (2008), open circles; Perna et al. (2009), filled circles; Thirouin et al. (2010), open squares; Mommert et al. (2012), asterisks; Santos-Sanz et al. (2012), stars; Thirouin et al. (2012), filled triangles; Nimmo et al. (2017), open triangles.

This may be caused by generally higher angular momentum in the Kuiper belt. Noteworthy, the majority of Main-belt asteroids are found to have double-peaked light curves caused by elongated shape (e.g. Marchis et al. 2006; Chiorny et al. 2007; Shevchenko et al. 2009; Szabó et al. 2016).

Moreover, there is a certain correlation between the light-curve amplitude and solar phase angle, i.e. light-curve amplitudes tend to be smaller at smaller phase angles, and light-curve shape effects are more pronounced at larger phase angles of about 20° (Zappala et al. 1990; Kaasalainen & Torppa 2001). And indeed, from ground-based sites TNOs can be observed only at small solar phase angles of less than a few degrees. As a result, TNOs with the same elongation would have smaller amplitude compared to that of a Main-belt asteroid. We also would like to emphasize that as Main-belt asteroids are closer to the observer than TNOs, their aspects of observations are changing a lot, and therefore it is easier to detect shape irregularities. Thus, considering these points, we suggest that more distant small bodies also tend to have aspherical shapes.

From our data sample (which is quite limited) four out of nine (44 per cent) objects have an amplitude larger or about 0.15 mag and have light curves that can only be caused by elongated shape. For the rest of the objects we detect quite small amplitudes. However, as it was shown in Johansen, Youdin & Lithwick (2012) objects with sizes $D < 200$ km in the Main belt and with $D < 300$ km in the Kuiper belt cannot go through process of self-gravitation and acquire spherical shape. In our sample we have five objects that fall into that category, and two of them have amplitudes smaller than 0.15 mag. We did not find any correlations between rotational and orbital properties, though our data sample is quite small and further investigations on this are needed.

It was shown by Sheppard et al. (2008) that larger bodies tend to have larger densities. The authors argue this is due to change of porosity and/or rock/ice ratio. In order to find possible correlation and following Sheppard et al. (2008), Fig. 16 shows the density estimations (using both our data and values taken from the literature) as a function of absolute magnitude. Only objects larger than ∼200 km (that are considered to be in hydrostatic equilibrium) were

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used. We found a Pearson correlation coefficient $r = -0.38$, which lies within the 95 per cent confidence interval and is statistically significant. Thus, we can confirm the existence of a certain correlation.

5 CONCLUSIONS

We present new photometric observations of nine outer Solar system objects, six TNOs and three Centaurs. For five objects that were previously observed we combined the published and new data and obtained more accurate rotation periods for three of them. Rotational period value for (281371) 2008 FC76 was reported for the first time. For above-mentioned six objects we were also able to estimate the lower limits of density values. By adding literature density values to our data set we confirm the existence of a previously reported density/absolute magnitude (or object size) trend.

For three objects which were observed during single nights we were able to estimate a lower limit of the rotational period values and light-curve amplitudes. We argue the existence of a light-curve asymmetry for (120178) 2003 OP32 caused by an elongated shape. The rest of the objects exhibit low amplitudes just above the noise level. We were not able to detect any light-curve asymmetry for them. None the less, we expect, that most of the TNOs and Centaurs population have double-peaked light curves caused by (at least slightly) elongated shape.

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