Abstract

Here we present the results of visible range light curve observations of ten Centaurs using the Kepler Space Telescope in the framework of the K2 mission. Well defined periodic light curves are obtained in six cases allowing us to derive rotational periods, a notable increase in the number of Centaurs with known rotational properties.

The low amplitude light curves of (471931) 2013 PH$_{44}$ and (250112) 2002 KY$_{14}$ can be explained either by albedo variegations, binarity or elongated shape. (353222) 2009 SY$_{6}$ and (499522) 2010 PL$_{66}$ could be rotating elongated objects, while 2017 CX$_{33}$ and 2012 VU$_{85}$ are the most promising binary candidates due to their slow rotations and higher light curve amplitudes. (463368) 2012 VU$_{85}$ has the longest rotation period, P = 56.2 h observed among Centaurs. The P > 20 h rotation periods obtained for the two potential binaries underlines the importance of long, uninterrupted time series photometry of solar system targets that can suitably be performed only from spacecraft, like the Kepler in the K2 mission, and the currently running TESS mission.

Keywords: methods: observational — techniques: photometric — minor planets, asteroids: general — Kuiper belt objects: individual: (250112) 2002 KY$_{14}$, (353222) 2009 YD$_{5}$, (514312) 2016 AE$_{193}$, (471931) 2013 PH$_{44}$, (463368) 2012 VU$_{85}$, (472760) 2015 FZ$_{117}$, (514312) 2016 AE$_{193}$, (523798) 2017 CX$_{33}$

1. Introduction

Centaurs are small solar system objects on non-resonant, giant planet crossing orbits (Gladman et al., 2008), which leads to frequent encounters with the giant planets and results in short dynamical lifetimes. Their origin is the Kuiper belt or the scattering disk, forming a bridge between the transneptunian objects (TNOs) and Jupiter–family comets (Tiscareno & Malhotra 2003; Di Sisto & Brunini 2007; Bailey & Malhotra 2009). Due to their relative proximity they provide an insight into the properties of outer solar system objects at the size scale of ~10-100 km (Duffard et al., 2014), which is currently unaccessible in the more distant transneptunian region by typical ground-based observations. Light curve observations and accurate determination of rotational periods of Centaurs are rare. In the recent review by Peixinho et al. 2020 there are 20 Centaurs with reliable light curve properties.

In several cases brightness variations were reported, but no definite periods could be derived, e.g. in the case of 2010 RF$_{43}$ or 2010 TY$_{53}$ (Bencen & Sheppard 2013); or (148975) 2001 XA$_{228}$ and (315898) 2009 QD$_{4}$ (Hromakina et al. 2018). This could be due to a common effect of low light curve amplitudes and the faintness of the targets, and/or due to rotation periods longer that could be deduced from typical ground-based observations due to the limited length of the observing blocks.

As described in Peixinho et al. 2020 Centaurs typically rotate faster than transneptunian objects (mean rotation periods of 8.1 h and 8.45 h, respectively. Peixinho et al. 2020, Thirouin & Sheppard 2019) and they do not show the
correlation between light curve amplitude and absolute magnitude observed among transneptunian objects (Duffard et al. 2009; Benedicchi & Sheppard 2013), which might be explained by the different collisional evolution of small and large transneptunian objects (Davis & Farinella 1997).

Periodic light curve variations of a single body can be due to elongated shape or albedo variegations on the surface, or the combination of the two. For minor planets, below the dwarf planet size limit (radius of ~200–300 km, Lineweaver & Norman 2010), light curve variation in most cases is explained by shape effects. Binaries can be identified with high probability from light curves only in those special cases when we see a contact binary system under a sufficiently high aspect angle, and binarity is confirmed by multiple epoch observations (Lacerda & Jewitt 2007). Light curves due to a deformed shape are often interpreted through equilibrium states of a strengthless body ("rubble-pile") in which case the shape is a Jacobi ellipsoid with a well-defined rotation period for a specific density. This equilibrium density is rather a lower limit for a real object with non-zero internal strength. A rotation period notably shorter than the equilibrium value (typically P > 1 d, see a detailed discussion in Sect. 4.2) can be interpreted as an indication of a binary system (Leone et al. 1984; Thirouin et al. 2010; Benedicchi & Sheppard 2013).

There are only two binary Centaurs identified so far: (65489) Ceto-Phorcys and (42355) Typhon-Echidna, both through direct imaging. We have to note here that there is some ambiguity in the definition of the Centaurs as a dynamical class. According to the historical definition Centaurs are objects in the giant planet realm whose evolution is currently not controlled by Jupiter (see the discussion in Gladman et al. 2008). A simple definition is that the semi-major axes of their orbits are between that of Jupiter and Neptune. The Gladman et al. (2008) dynamical classification scheme uses an additional criterion that a Centaur has to have a perihelion distance q > 7.35 AU and a Tisserand parameter of T_J > 3.05 to distinguish these objects from Jupiter family comets. In this scheme e.g. (60558) Echeclus (q = 5.8 AU, T_J = 3.03) and (52782) Okyrhoe (q = 5.8 AU, T_J = 2.95), which are traditionally considered as Centaurs, are classified as 'Jupiter coupled'. The two binaries mentioned above, Ceto-Phorcys and Typhon-Echidna, are classified as Centaurs by the Deep Ecliptic Survey (Elliot et al. 2005), but are considered as scattered disk objects according to Gladman et al. (2008). We consider them here as these are the only known binaries which are at least dynamically close to the Centaur group, and they are also listed in the recent review of Centaurs by Peixinho et al. (2020).

Dotto et al. (2008) found a rotation period of 4.43±0.03 h and a light curve amplitude of 0.13±0.02 mag for Ceto-Phorcys. This is an unexpected result, as according to Grundy et al. (2007) this is a tidally evolved and spin locked binary system, with a small orbital eccentricity (e ≤ 0.013) and orbital period of P = 9.554 d. The Typhon-Echidna system is the other known binary Centaur, discovered by Noll et al. (2006), with an orbital period of P_orb = 18.98 and semi-major axis of a = 1629 km (Grundy et al. 2008). In contrast to Ceto-Phorcys the binary orbit of Typhon-Echidna is rather eccentric (e = 0.53), showing that this is not a tidally evolved system. Thirouin et al. (2010) obtained a tentative rotation period of P_rot = 9.67 h and a small light curve amplitude of Δm = 0.07±0.01, consistent with other studies reporting on nearly flat light curves (Ortiz et al. 2003; Sheppard & Jewitt 2003).

A large fraction of binaries originally in high eccentricity orbits can evolve to circular and very tight orbits due to Kozai effects (Porter & Grundy 2012). An originally triple system that loses a component will also end up in a very tight pair (Margot et al. 2015). The angular resolution of the Hubble Space Telescope – that has detected most of the known transneptunian and Centaur binaries – allows the detection of a nearly equal brightness binary with a semi-major axis of ~400 km at 10 AU (typical perihelion distance of Centaurs); proportionally wider systems can be discovered at larger heliocentric distances. Due to the lack of suitable spatial resolution more compact systems can typically be discovered through the detection of their characteristic light curves; i.e. large, Δm ≥ 1 mag amplitudes with U-shaped maxima and V-shaped minima (see e.g. Thirouin & Sheppard 2018 for a discussion of contact binary systems in the plutoino population). In some rare cases binary nature can be deduced from stellar occultation observations, as in the case of 2014 MU₆₈ (Moore et al. 2018).

As suggested by Thirouin & Sheppard (2018), nearly half of the plutoino population may be contact or a tight binary system. Since plutinos are thought to be one of the parent populations of Centaurs (Di Sisto et al. 2010), one can expect a similar abundance of contact and tight binaries in the Centaur population, too, assuming that tight systems remains intact in giant planet encounters.

Studies of a large sample of minor planet light curves observed in the framework of the K2 mission of the Kepler Space Telescope (Howell et al. 2014) showed an overabundance of long (up to several days) rotation periods among main-belt asteroids (Szabó et al. 2016; Molnár et al. 2018). In the case of Jovian Trojans a binary fraction of 6–36% (Ryan et al. 2017) and ~20% (Szabó et al. 2017) was estimated from the data. These studies were carried out in the course of systematic programs in the K2 mission, aimed at obtaining light curves of solar system targets, including
Table 1: Summary of K2 light curve observations of our Centaur sample. The columns are: Name – provisional designation of the target; Cam. – K2 campaign number; Start – Start date of the K2 observations (Julian date); End – End date of the K2 observations (Julian date); Length – total length of the observations (day); Duty cycle – fraction of frames used for light curve photometry; \( r_\alpha \), \( \Delta \) – heliocentric distance, target to observer distance and phase angle range during K2 measurements; \( m_{R}^{11} \) and \( m_{R}^{11}_\text{ph} \) – phase angle uncorrected and corrected USNO B1.0 R-band absolute magnitude of the targets, derived from our K2 observations.

| Name        | Cam. | Start (JD) | End (JD) | Length (day) | #frame | Duty cycle | \( r_\alpha \) (AU) | \( \Delta \) (AU) | \( \alpha \) | \( m_{R}^{11} \) (mag) | \( m_{R}^{11}_\text{ph} \) (mag) |
|-------------|------|------------|----------|--------------|-------|------------|------------------|----------------|---------|-----------------|-----------------|
| 2002 K1 14  | C04  | 2457669.6537 | 2457679.5845 | 9.931         | 300   | 0.617      | 16.787...16.791 | 16.349...16.501 | 3.230...3.400 | 8.48±0.17     | 9.43±0.10       |
| 2009 YD 3   | C16  | 2458100.3852 | 2458120.1721 | 19.637         | 867   | 0.902      | 14.869...14.906 | 14.474...14.762 | 3.429...3.788 | 10.13±0.27    | 9.75±0.27       |
| 2009 YD 3   | C18  | 2458263.4745 | 2458302.3800 | 38.905         | 1401  | 0.734      | 15.125...15.204 | 14.499...15.169 | 3.086...3.909 | 8.25±0.25     | 7.99±0.25       |
| 2010 GX 14  | C11  | 2457669.6357 | 2457679.5845 | 9.931         | 300   | 0.617      | 16.787...16.791 | 16.349...16.501 | 3.230...3.400 | 8.48±0.155    | 8.14±0.156      |
| 2010 HJ 24  | C11  | 2457682.7721 | 2457692.8663 | 10.094         | 395   | 0.800      | 23.994...24.000 | 23.644...23.814 | 2.320...2.405 | 7.06±0.75     | 6.81±0.75       |
| 2010 PL 88  | C12  | 2457762.8210 | 2457799.6318 | 45.281         | 1148  | 0.518      | 21.553...21.616 | 21.042...21.732 | 2.151...2.591 | 8.25±0.25     | 7.99±0.25       |
| 2012 VU 15  | C12  | 2458580.1437 | 2458800.8963 | 30.753         | 1022  | 0.679      | 15.583...15.588 | 15.073...15.577 | 3.148...3.594 | 8.39±0.44     | 8.16±0.45       |
| 2013 PH 44  | C13  | 2457756.1287 | 2457786.1048 | 29.976         | 859   | 0.586      | 24.735...24.767 | 24.334...24.813 | 2.078...3.239 | 9.53±0.21     | 9.17±0.22       |
| 2015 FZ 117 | C15  | 2458179.5332 | 2458246.4125 | 66.879         | 1108  | 0.638      | 14.694...14.781 | 13.997...14.956 | 2.507...3.823 | 10.60±0.47    | 10.24±0.47      |
| 2016 AE 193 | C16  | 2458122.4827 | 2458151.3711 | 28.689         | 1245  | 0.887      | 16.977...16.996 | 16.508...16.965 | 2.907...3.339 | 8.64±0.17     | 8.31±0.17       |
| 2017 CX 13  | C18  | 2458288.2605 | 2458298.2321 | 9.972          | 379   | 0.773      | 10.675...10.685 | 10.377...10.549 | 5.366...5.537 | 11.33±0.30    | 10.68±0.30      |

main belt asteroids (Szabó et al., 2015, 2016), Berthier et al. (2016), Molnár et al. (2018), Jovian Trojans (Ryan et al., 2017), transneptunian objects (Pál et al., 2015, 2016), Beneccia et al. (2018) and irregular moons of giant planets (Kiss et al., 2016, Parkas-Takács et al., 2017). These observations provided continuous light curves which had significantly longer time-spans (up to 80 days) than ground-based measurements and therefore could break the ambiguity of rotational periods caused by daily aliases.

In this paper we report on observations of ten Centaurs: (250112) 2002 KY14, (353222) 2009 YD7, (499522) 2010 PL66, (463368) 2012 VU85, (471931) 2013 PH44, (472760) 2015 FZ117, (514312) 2016 AE193, and (523798) 2017 CX13 observed with Kepler in the K2 campaigns. One target, (250112) 2002 KY14, has previous light curve measurements, and for this target we provide an updated, more accurate rotation period and light curve. The other nine Centaurs have no light curve measurements reported in the literature. Due to poorly constrained light curve properties for four targets we add reliable measurements for five objects to the group of Centaurs with known rotation periods and light curves. We also perform simple calculations to deduce whether the light curve variation of our targets can be caused more likely by shape effects or binarity.

2. Observations, data reduction and photometry

Kepler observed numerous Solar System objects during the K2 mission. The observing strategy and data reduction steps of centaurs have been analogous to other TNO and asteroid targets that we previously published (Pál et al., 2015, Kiss et al., 2016, Molnár et al., 2018). Since Kepler observed only selected pixels during each 60-80 d long Campaign, pixels over ~ 30 d long arcs of the apparent trajectories of the target were allocated for each Centaur (see Fig. 1 for an example).

We processed the Kepler observations with the fitsh software package (Pál, 2012). First, we assembled the individual Target Pixel Files of both the track of the target and that of the nearby stars into mosaic images. Astrometric solutions were derived for every mosaic frame in the campaign, using the Full Frame Images (acquired once per campaign) as initial hints, and the individual frames were registered into the same reference system. We then enlarged the images by roughly 3 times, and transformed them into RA-Dec directions. This enlargement helped to decrease the fringing of the residual images in the next step, where we subtracted a median image from all frames. The median was created from a subset of frames that did not contain the target. We applied simple aperture photometry to the differential images based on the ephemeris provided by the JPL HORIZONS service.

We then discarded data points that were contaminated by the residuals of the stellar images, saturated columns and crosstalk patterns from the camera electronics – this is characterised by the duty cycle, the ratio of the number of frames used for the final light curve derivation and the total number of frames on which the target was theoretically visible. While this ratio is typically well above 50%, it is only ~34% for 2015 FZ117, which was very faint, and thus

---

1We use the provisional designations to identify our targets throughout the paper
very sensitive to any structures in the background. We had to discard a large number of frames that were affected by stellar residuals, crosstalk patterns, or in which the object was not detected.

The light curves obtained were analysed with a residual minimization algorithm (Pál et al. 2016; Molnár et al. 2018). In this method we fit the data with a function \[ A + B \cos(2\pi f \Delta t) + C \sin(2\pi f \Delta t), \] where \( f \) is the trial frequency, \( \Delta t = T - t \), \( T \) the approximate center of the time series, and \( A, B, \) and \( C \) are parameters to be determined. We search for the minimum in the dispersion curves for each frequency. As demonstrated in Molnár et al. (2018) the best fit frequencies obtained with this method are identical to the results of Lomb–Scargle periodogram or fast Fourier transform analyses, with a notably smaller general uncertainty in the residuals.

3. Results

3.1. Absolute magnitudes

We determined the absolute magnitudes of the targets, transformed from the K2 observations to the USNO B1.0 R-band photometric system (Monet et al. 2003), in the same way as in Pál et al. (2015). We calculated both the phase angle uncorrected (\( m_R^{11} \)) and phase angle corrected (\( m_R^{110} \)) absolute magnitudes. As the phase angle ranges of the observations were rather small (a maximum of 1.7 in the case of 2002 KY\textsubscript{14}) we could not fit a phase angle correction curve when calculating \( m_R^{110} \), but used a \( \beta_R = 0.104 \pm 0.074 \) mag deg\(^{-1} \) linear phase angle correction, obtained as the median values of the R-band correction factors of Centaurs in Ayala-Loera et al. (2018). While there is a specific phase correction coefficient determined for 2002 KY\textsubscript{14}, it is based on sparse and uncertain data (Alvarez-Candal et al., 2016), therefore we used the coefficient above even in this case. These absolute magnitudes are listed in Table 1 along with the basic observational parameters, using data from the Minor Planet Center.

3.2. Light curves

We were able to determine light curve periods from the periodograms for six targets. The folded light curves and residual dispersion plots are presented in Fig. 2 and the rotation periods and light curve amplitudes observed are summarized in Table 2.

In all cases we accepted the most prominent peak in the phase dispersion versus frequency plot as the actual primary light curve period. The quality of the light curve frequency/period determination is characterised by the accuracy of the frequency determination (converted to period uncertainty (h) in Table 2), and also by the ratio of the light curve peak over the r.m.s. of the phase dispersion at other frequencies. This latter was calculated for the whole frequency range investigated (\( S_0 \)) and also for a narrower frequency range of \( \pm 1 \) d\(^{-1} \) around the peak (\( S_{fp} \) in Table 2).
Period and amplitude uncertainties were also calculated with the FAMIAS and Period04 methods using Fourier-transforms (Lenz & Berger 2004, Zima 2008). We calculated the formal least-squares uncertainties with both softwares, plus the Monte Carlo module of Period04 that generates sets of artificial data with randomized noise based on the residual light curve, and tries to fit them with the input frequency set. The latter method gave elevated uncertainties in three cases, most notably for 2012 VU₄₄ and 2013 PH₄₄, due to the low signal-to-noise ratio of the fitted frequency and the large scatter of data points. We also calculated the relative uncertainties for the main frequency components that generally agreed with the error estimates for the full amplitudes. We chose the larger of these estimates for each target (see the period and uncertainties in Table 2).

To characterise the possible double peak nature we folded the light curves with the double peak period and calculated the significance $S_d$ of the difference between the two light curve halves (phases $0 \leq \phi < 0.5$ and $0.5 \leq \phi < 1$) following Pal et al. (2016) (see eqs. 2, 3 and 4). These significance values were calculated for a series of bin numbers $N = 16...24$ which resulted in only slightly different $S_d$ values for the same target. The actual mean $S_d$-s are listed in Table 2. Following Pal et al. (2016) we used the criterion that for a detectable double peak behaviour $S_d \geq 3$. In our sample only 2016 AE₁₉₃ has $S_d = 1.8$, for all other targets $S_d > 3$, indicating that a double peak light curve is likely in these latter cases.

3.3. Discussion of the individual targets

(250112) 2002 KY₁₄ was discovered in 2002 by Trujillo, C. A. & Brown, M. E., Thirion et al. (2010) reported on a single peak rotational period of 3.56 h or 4.2±0.05 h with an amplitude of 0.13±0.01 mag. Duffard et al. (2014) modeled the thermal emission of 2002 KY₁₄ using Herschel/PACS measurements of the "TNOs are Cool!" Open Time Key Program, using a NEATM model with fixed beaming parameter of $\eta = 1.2$, and obtained an effective diameter and albedo solution of $D = 47^{+3}_{-1}$ km and $p_V = 5.7^{+1.4}_{-1.7}$%. Our new rotation period is $P = 8.4996\pm0.0036$ h, with an asymmetric, double peak light curve. The amplitude of the first maximum is $\Delta m_1 = 0.090\pm0.009$ mag, with a secondary maximum of $\Delta m_2 = 0.028\pm0.008$ mag, i.e. the first peak is taller by 0.062 mag. The new spin period is the double period of the 4.2 h found by Thirouin et al. (2010).

(353222) 2009 YD₇ was observed in the K2 missions in two campaigns, C16 and C18 (see also Table 1). A well defined, double peak light curve is obtained with a period of $P = 10.1590\pm0.0008$ h, and two similar light curve amplitude peaks of $\Delta m = 0.202\pm0.028$ mag and $\Delta m = 0.180\pm0.034$ mag. For (463368) 2012 VU₄₅ we obtained a light curve with a period of $P = 28.12\pm1.66$ h and light curve amplitude of $\Delta m = 0.38\pm0.05$ mag, assuming a single peak light curve. If the double peak light curve is considered ($P = 56.2$ h), it is the Centaur with the longest rotation period ever observed. The double peak period seems to be more likely due to the different first and second peaks observed in the double peak light curve ($S_d = 3.2$).

A single peak light curve of (471931) 2013 PH₄₄ is detected with a period of $P = 11.08\pm0.12$ h, and light curve amplitude of $\Delta m = 0.15\pm0.04$ mag. With the corresponding $P = 22.16\pm0.24$ h double peak period the light curve is notably asymmetric, as presented in Fig. 2, making the double peak period more likely.

(514312) 2016 AE₁₉₃ has a single peak light curve with a period of $P = 4.556\pm0.013$ h, and light curve amplitude of $\Delta m = 0.228\pm0.014$ mag. The double period light curve shows no significant asymmetry, and the light curve amplitude parameter derived (S_d = 1.8, see above) indicates that the light curve is rather single peak (a light curve folded with the double peak period is presented in Fig. 2 for consistency). However, this does not exclude that the double peak period is the rotation period of this target. E.g. a sufficiently symmetric triaxial ellipsoid – often used in simple asteroid shape modelling – produces a light curve with two identical half periods.

(523798) 2017 CX₃₃ is moving on a very high inclination orbit (see Table 2). It has a rotation period of $P = 21.51\pm0.13$ h (double peak) with a light curve amplitude of $\Delta m = 0.27\pm0.11$ mag. For four of our targets no unambiguous rotation period could be obtained ((499522) 2010 PL₆₆, 2010 GX₃₄, 2010 JJ₂₆, (472760) 2015 FZ₁₇, see Fig. 3). For these objects we provide an upper limit on the light curve amplitude only (see Table 2). As seen in Fig. 3 the Fourier amplitude depends strongly on the spin rate – there is a significant increase towards smaller frequencies / longer light curve periods, i.e. a light curve could have been detected at higher frequencies with a smaller amplitude, and we more likely miss light curve periods if $P \geq 1$ d for these targets.

Altogether we add one updated light curve (2002 KY₁₄), and five new ones to the list of Centaurs with known light curve properties, previously containing 20 targets (Peixinho et al. 2020).
Figure 2: The observed light curve (left), the phase curve (middle), in all cases folded with the most probable period (middle), and the residual dispersion versus frequency plot (left). In the middle column the color scale represents dates, BJD-2450000, as indicated at the side of the figures. In the normalised residual plots red arrows mark the primary periods detected.
Figure 3: The observed light curve (top row) and the corresponding Fourier amplitude plots (bottom row) of those three Centaurs (2010 PL66, 2010 GX34 and 2010 JJ124) for which no rotation period could be obtained. Fourier amplitude plots are presented here instead of the dispersion residual plots as these were used to estimate the amplitude upper limits in the case of targets with no light curve period detected.

Figure 4: Likely rotation periods of Centaurs in the literature and in our present work, sorted by increasing rotation period. The bar colours correspond to: red — literature, single peak period; orange — this study, single peak period; light blue — literature, double peak period; dark blue — this study, double peak period. In the case of single peak periods we also include the double peak periods with dashed lines.
3.4. Comparison with Centaurs with known light curves

The most recent review by Peixinho et al. (2020) lists light curve periods for 20 Centaurs including 2002 KY14 (2007 UL126), and we have considered this sample as a reference sample for a comparison with our targets. The targets included are: (2060) Chiron, (5145) Pholus, (7066) Nessus, (8405) Asbolus, (10199) Chariklo, (31824) Elatus, (32532) Thereus, (42355) Typhon, (52872) Okyrhoe, (55567) Amycus, (65489) Ceto, (83982) Crantor, (95626) 2002 GZ, (120061) 2003 CO, (136204) 2003 WL7, (145486) 2005 UJ, (281371) 2008 FC, etc. We used the preferred single peak or double peak light curve periods as rotation periods as given in Peixinho et al. (2020), counter checked with the original papers (see the references in Peixinho et al., 2020). Note that the period of 8.32 h for 2005 UJ is the double peak period according to Thirouin et al. (2010), and that for Ceto and Typhon the light curves periods used here are not the binary orbital periods, as discussed in Sect. 1.

We compare the rotation periods of the Centaurs in the reference sample with our targets in Fig. 4. Our targets are presented in this plot with their preferred single or double peak periods, as discussed in Sect. 3.2 above.

Using the rotation periods as presented in Fig. 4 the Centaurs with the three longest rotation periods are from our sample (2017 CXs, 2013 PH64, 2012 VU38). When considering double peak periods for all targets, however, there are several other objects with similar rotation periods (Typhon, Crantor, Amycus, Echeclus, Elatus). The single important feature is the quite long, $P = 9.2$ h (8.9 h without our targets), which is now between the mean rotation period of the cold classicals (9.48 ± 1.53 h) and the rest of the TNOs (8.45 ± 0.58 h), as obtained by Thirouin & Sheppard (2019). The TNO sample in the Light Curve Database (LCDB Warner et al., 2009) has a spin rate distribution rather similar to that of Centaurs (red curve in Fig. 5), with a median rotation period of $P = 8.84$ h. A Maxwellian fit to the spin rate distribution (see e.g. Pravec & Harris, 2000 for a discussion) seems to be an acceptable model as it provides a reduced-$\chi^2$ value of ≤ 1, using the square root of the number of objects in the specific bins as uncertainties.

4. Rotating elongated bodies versus binarity

4.1. Density estimates from Jacobi ellipsoid models

Leone et al. (1984) and Sheppard & Jewitt (2004) identified three main zones on the light curve amplitude versus rotational frequency plane (see Fig. 6), re-evaluated by Thirouin et al. (2010) and Benecchi & Sheppard (2013). Light curve variations of objects with small amplitudes ($\Delta m \leq 0.25$ mag or 0.15 mag) can either be caused by albedo and shape features or can as well be binaries (region A in Fig. 6). If the rotational equilibrium of a strengthless body is considered and approximated by a Jacobi ellipsoid, constant density curves can be drawn (blue dash-dotted curves in Fig. 6). We list the densities estimated this way for our targets in the last column of Table 3 following Lacerda & Jewitt (see eqs. 1 & 2 in 2007 and references therein), assuming $\theta = \pi/2$ aspect angle, i.e. equator-on viewing geometry and maximum light curve amplitude. Objects to the right of a curve of a constant density (e.g. 0.3 g cm$^{-3}$ for Centaurs, region B) are likely rotating single bodies, if their rotational speed is below the breakup limit (4.0 cycle day$^{-1}$ for 0.3 g cm$^{-3}$). The rotation of the objects to the left is too slow to cause elongation and a corresponding rotational light...
Figure 5: Histogram presenting the spin rate distribution of Centaurs with our targets included, as a function of normalised spin rate (blue bars). The red curve represents the spin rate distribution of transneptunian objects as obtained from the LCDB, normalised to the total number of Centaurs in our sample. The black solid curve shows the Maxwellian fit to the Centaur data.

Figure 6: Light curve amplitude versus frequency of the reference sample Centaurs (black dots) and our six targets (red dots). Blue dash-dotted curves represent the rotational frequencies and light curve amplitudes corresponding to the rotation of a strengthless body, modeled as Jacobi ellipsoids, of a specific density. The densities of the curves are shown at the top in g cm$^{-3}$ units. In the blue and purple shaded areas (below $\delta m \leq 0.25$ or 0.15 mag, region A) light curves can be explained either by albedo variegations, deformed shape or binarity. Targets in the red shaded area (region B), right of the $\rho = 0.3$ g cm$^{-3}$ curve, could be elongated due to rotation. Objects in region C should have densities notably below $\rho = 0.3$ g cm$^{-3}$ in order to be elongated from rotation, and can be considered as binary candidates (see the text for a detailed discussion).
curve. For these objects the light curves are often explained by binarity (e.g. Leone et al., 1984; Sheppard & Jewitt, 2004).

For three of our targets the estimated Jacobi ellipsoid densities are in the order of $\sim 0.5 g cm^{-3}$ ($\rho_{JE} = 0.54, 0.39$ and $0.48 g cm^{-3}$ for 2002 KY$_{14}$, 2009 YD$_{7}$ and 2016 AE$_{193}$, respectively, see Table 3), inside the range expected for smaller (D < 500 km) transneptunian objects and Centaurs (Grundy et al., 2019; Kiss et al., 2019). The Jacobi ellipsoid density estimates are, on the other hand, notably lower for 2012 VU$_{85}$, 2017 CX$_{13}$ and 2013 PH$_{44}$ ($\rho_{JE} < 0.1 g cm^{-3}$), outside the range of densities plausibly considered, indicating that the light curves in these cases cannot be explained by equilibrium figures of rotating strengthless bodies. As discussed above, objects in this part of the light curve amplitude vs. rotational frequency plot may be considered as binaries. However, due to the low amplitude ($\Delta m \leq 0.15$ mag) the light curves of 2002 KY$_{14}$ and 2013 PH$_{44}$ may as well be explained by albedo variegations on the surface, in addition to possible binarity or elongated shape. Also, the light curve amplitude of 2016 AE$_{193}$ is below the 0.25 mag limit originally considered for surface variegations.

4.2. Characterisation of potential binarity

It is a question in the case of a binary whether the observed rotation period is the common, synchronised period of a binary, or if we can see the light curve of a single body, rotating with an angular speed different from the orbital one. In the main belt small binary asteroids (D $\leq$ 10 km) are typically asynchronous if their rotation period is P $\leq$ 8 h (Pravec & Harris, 2007). Synchronous binaries are found for P $\geq$ 8 h, usually at the D $\approx$ 10 km sizes, but there are synchronous systems with D $\approx$ 100 km as well ((90) Antiope and (617) Patroclus-Menoetius), bracketing the size range of the Centaurs in our sample. Large asteroids (D $\geq$ 100 km) with small satellites also typically rotate faster (P $\leq$ 8 h) Pravec & Harris, 2007.

In the plutino population, a likely parent population of Centaurs, Thirouin & Sheppard (2018) estimated that the incidence rate of contact binaries could be as high as $\sim$50%. In the transneptunian region there is an overabundance of nearly equal-brightness (and therefore probably nearly equal-mass) binaries among the resolvable systems (Noll et al., 2008), and a large fraction, even close to 100% among cold classical Kuiper belt objects (Noll et al., 2014; Fraser et al., 2017).

While we cannot unambiguously identify a binary system from the light curve and rotation period alone, a simple check can be performed to show whether a specific system could potentially be a binary based on its light curve period and absolute magnitude. To characterise a system in this way we use the estimated ‘separation’, $a_{bin}$, the semi-major axis of the orbit of the potential binary. We assume that the binary has two equally sized and equal mass components (Noll et al., 2008). In the case of our Centaur reference sample we used the radiometric size estimates based either on Herchel/PACS (Duffard et al., 2014; Fornasier et al., 2013) or WISE (Mainzer et al., 2016) observations, whenever these were available; when radiometric size was not available we simply used the default size (or albedo and absolute magnitude) estimate in Peixinho et al. (2020), and used this value to calculate the binary diameters and volumes (see e.g. Vilenius et al., 2014). The binary separation, $a_{bin}$ is obtained from Kepler’s third law, assuming a density of 0.7 g cm$^{-3}$ to obtain the mass, characteristic for 10-100 km-sized Kuiper belt bodies and Centaurs (see e.g. Grundy et al., 2019; Kiss et al., 2019) for a latest compilation of Kuiper belt densities). The densities estimated for Ceto-Phorcys ($\rho = 1.37^{+0.35}_{-0.35} g cm^{-3}$ (Grundy et al., 2007) and Typhon-Echinda ($\rho = 0.44^{+0.44}_{-0.17} g cm^{-3}$ Grundy et al., 2008) are at the lower/upper extremes of the densities of $\sim 100$ km-sized objects, and therefore may not be representative for the whole population.

We present the rotational frequency (cycle day$^{-1}$) as a function of the estimated size in Fig. 7 (upper panel), and compare it with other Centaurs (black dots) and with the population of transneptunian objects (TNOs), the latter ones taken from the LCDB. As seen previously in the rotation period comparison, the rotational frequencies of our targets are typically lower than those of other Centaurs and TNOs.

We used the ratio of $a_{bin}$ to the effective diameter D$_{0}$ of the two equally sized bodies to characterise the potential binarity (see Taylor & Margot, 2011 for a more complex tidal evolution analysis using this parameter). For having enough space for two bodies in such a system $a_{bin}/D_{0} > 1$ has to be fulfilled ($a_{bin}/D_{0} = 1$ corresponds to a contact binary). As shown in Fig. 7 $a_{bin}/D_{0} < 1$ for many slower rotating Centaurs, but there are no objects with $a_{bin}/D_{0} \geq 2$ in the Centaur reference sample. Note that ‘classical’ binary systems with tidal locking do not appear in these plots, as their rotational/orbital periods are notably longer (several days) than the typical rotation periods observed from light curves. These known binary systems also have notably larger separations than that can be deduced for a typical
light curve target. The same calculations were performed for our targets. Radiometric size estimate is available for 2002 KY$_{14}$ only (Duffard et al., 2014), in the other cases we used our calculated R-band absolute brightness ($m_R^{\text{ff}}$), and assumed a specific colour to obtain the $H_V$ V-band absolute magnitude. The colour distribution of Centaurs is bimodal (e.g. Peixinho et al., 2012; 2015) and the two colour groups correspond to two different average albedos (Lacerda et al., 2014; Farkas-Takács et al., 2018). For our targets we have colour information for 2012 VU$_{85}$ and 2002 KY$_{14}$ (Teleg et al., 2016; Wong et al., 2019), but as mentioned above, 2002 KY$_{14}$ has a reliable size estimate from radiometry. For 2012 VU$_{85}$ (Teleg et al., 2016) obtained V-R = 0.63±0.04 mag, and with this colour 2012 VU$_{85}$ is in the ‘bright-red’ group identified by Lacerda et al. (2014) which has a mean albedo of $p_V = 0.16±0.08$. We used this value to obtain the effective diameter of 2012 VU$_{85}$ from the absolute magnitude. As we have no colour information for the other four targets we used a mean V-R = 0.558 mag and $p_V = 0.88$, obtained from the Centaur sample with known geometric albedos (Duffard et al., 2014; Farkas-Takács et al., 2018), averaged over the two colour groups. The lack of colour information introduces a V-R error of ∼0.18 mag in the $H_V$ estimate (Peixinho et al., 2015).

Interestingly, three of our targets, 2013 PH$_{14}$ 2017 CX$_{33}$ and 2012 VU$_{85}$ have $a_{bin}/D_0 \gtrsim 2$, exceeding the values of the slowest rotating Centaurs, and also our other three targets have $1 \lesssim a_{bin}/D_0 \lesssim 2$, in the same range as the slower rotating Centaurs. Based on this estimate our six targets with rotation periods might be considered as potential binaries concerning this parameter only. However, as discussed above, a distorted rotating body or albedo variegations may also be plausible explanations for 2002 KY$_{14}$, 2009 YD$_7$ and 2016 AE$_{193}$.

4.3. Tidal evolution timescales

The simple calculations above assumed that the observed light curve period were both the rotation period and the orbital period of the binary, i.e. the system was tidally locked. It is, however, an important question whether the rotation of the individual bodies could have been slowed down by tidal forces and synchronized to the orbital period. Tidal dissipation is governed by the internal structure and composition of the bodies, and is usually considered equal (e.g. Gladman et al., 1996) we obtain $Q_\star$ = 300–3 × 10$^9$ using $Q = 100$ for the Ceto-Phorcys system, in which the two bodies were in the 100-200 km size range. For our small Centaurs this correction is even more significant. Assuming $\mu = 4 \times 10^7$ Pa rigidity (that of icy bodies, see e.g. Gladman et al., 1996) we obtain $Q_\star \approx 10^7$ for all of our targets (actual values are listed in Table 3).

One of the important timescales related to the tidal evolution of binary systems is the orbit circularization timescale that we estimate as (Noll et al., 2008).

$$\tau_{\text{circ}} = \frac{4Q' M_2}{G^2 M_1} \left( \frac{a}{R_2} \right)^{1/2} \left( \frac{a}{R_2} \right)^5$$

where $a$ is the semi-major axis of the binary orbit, $M$ is the mass, $R$ is the radius of the object, and $G$ is the gravitational constant. The indices 1 and 2 refer to the primary and secondary, however, in our simple calculations all bodies are considered to be equal.

For our binary systems $\tau_{\text{circ}}$ obtained through these calculations are in the order of $10^4–10^5$ yr, using the present estimated parameters of the systems, significantly smaller than the age of the Solar System. Another important question is whether in these systems the individual bodies could keep at least some of their own spin angular momentum and rotate with a period different from that of the binary orbit, or are fully spin locked due to tidal effects. We estimate this despinning (or spin-locking) timescale following (Grundy et al., 2007), as:

$$\tau_{\text{spin}} = \frac{Q' \Delta \omega M_1 a^6}{G M_2^2 R_1^4}$$

11
Figure 7: Upper panel: Rotational frequency (cycle day$^{-1}$) versus the estimated diameter; Lower panel: $a_{\text{rel}}/D_0$ binary semi-major axis to size ratio versus the binary mass estimated. On both panels black and gray dots correspond to Centaurs from the reference sample and TNOs, respectively. Targets investigated in this paper are marked by red symbols.
\[
\Delta \omega t = \omega t_0 - \omega t
\]

where \(\Delta \omega t\) is the change in angular speed with respect to the initial value. When the spin locking state is reached the mean motion \(n\) of the binary orbit is assumed to be equal to the angular speed obtained from the light curve period, i.e. \(\Delta \omega t \approx \omega t_0 - \omega t\). For our targets the despinning timescales are \(10^7\)–\(10^8\) yr, typically a few times longer than the corresponding circularization timescale. This suggests a fast tidal evolution for basically all systems, on timescales much smaller than the age of the Solar system (see also Table 3).

Kozai cycle tidal friction (Porter & Grundy, 2012) is a mechanism that can also create tight systems from an originally wider system with high eccentricity, if the inclination of the binary orbit to the heliocentric orbit is sufficiently large.

### 4.4. Encounters with giant planets

Tenuously bound binaries may be disrupted by giant planet encounters and Centaurs are especially susceptible in this respect. For our assumed system configurations, however, the ratio of the calculated binary orbit semi-major axis to the Hill radius is \(a_{\text{bin}}/r_{\text{H}} \leq 0.0025\) for all our targets, while the Hill radii themselves are \(r_{\text{H}} \leq 0.001\) AU. Encounters that close should be extremely rare (Noll et al., 2006). Concerning the target with the largest \(a_{\text{bin}}\) in our sample, Wlodarczyk et al. (2017) investigated the dynamics of 2012 VU₈₅, including close encounters with the giant planets Uranus and Neptune. According to their analysis this Centaur has no encounters with Uranus closer than \(\sim 4\) AU, and with Neptune closer than \(\sim 1\) AU. For 10\% of the closest encounter distance with Neptune (0.1 AU) the gravitational influence distance of Neptune (Hill radius) would be \(\sim 10^4\) km, significantly larger than the estimated \(\sim 140\) km semi-major axis of the system, i.e. the binary system can be safely kept during these encounters (due to the similar mass and larger distances the encounters with Uranus are even safer).

### 5. Conclusions

We have presented Kepler Space Telescope light curve measurements of ten Centaurs, observed in the course of the K2 mission. We were able to derive rotation periods for six of these targets, of which five are new period determinations. Three of our six targets fall in the \(P \geq 20\) h regime, not seen previously in ground based light curve period studies of Centaurs.

Due to the low amplitudes the light curves of 2013 PH₄₄ and 2002 KY₁₄ can be explained either by albedo variegations, binarity or elongated shape. 2009 YD₇ and 2016 AE₁₉₃ are just above the amplitude limit and have relatively short rotation periods indicating that their light curves could be caused by elongated shape. Due to their slow rotations and higher light curve amplitudes 2017 CX₁₃ and 2012 VU₈₅ are the most promising binary candidates.

### Table 3: Estimated binary system mass, binary size, surface gravitational acceleration, binary orbit semi-major axis, tidal dissipation parameter, and circularization and despinning timescale for our targets (see the text for the details of the estimation). We also list the ratio of the estimated semi-major axis, \(a\), to the maximum semi major axis (\(a_{\text{max}}\)) for which despinning of the components can be expected within the lifetime of Solar system, 4.5\,10^9\) yr. The semi-major axis of the binary orbit and the tidal dissipation timescales cannot be estimated for targets without a known rotation period (bottom lines). Note that the system mass estimated for a binary is a factor of \(\sqrt{2}\) smaller than it would be for a single object. In the last column we list the estimated density assuming a single body with a shape of a Jacobis ellipsoid, considering the actual double peak light curve period and the observed light curve amplitude (also not obtained for targets without a known rotation period).

| Target   | Mass (kg) | \(R_0\) (km) | \(g\) (cm s\(^{-2}\)) | \(a\) (km) | \(Q'\) | \(\tau_{\text{circ}}\) (yr) | \(\tau_{\text{spin}}\) (yr) | \(\rho_{\text{sys}}\) (g cm\(^{-3}\)) |
|----------|-----------|--------------|------------------------|------------|------|-----------------------------|-----------------------------|-------------------------------|
| 2002 KY₁₄ | 2.7E+16   | 16.6         | 0.6                    | 34.8       | 5.1E+07 | 2.0E+04                     | 1.4E+05                     | 0.540                          |
| 2009 YD₇  | 1.7E+16   | 14.3         | 0.6                    | 33.8       | 6.8E+07 | 5.9E+04                     | 3.3E+05                     | 0.388                          |
| 2012 VU₈₅ | 1.5E+17   | 29.5         | 1.2                    | 137.4      | 1.6E+07 | 1.1E+06                     | 1.7E+06                     | 0.018                          |
| 2013 PH₄₄ | 3.8E+16   | 18.6         | 0.7                    | 74.1       | 4.0E+07 | 1.0E+06                     | 2.1E+06                     | 0.088                          |
| 2016 AE₁₉₃| 1.2E+17   | 27.6         | 1.1                    | 60.8       | 1.8E+07 | 9.9E+03                     | 6.4E+04                     | 0.480                          |
| 2017 CX₁₃ | 4.4E+15   | 9.1          | 0.4                    | 35.4       | 1.7E+08 | 3.8E+06                     | 7.8E+06                     | 0.094                          |
| 2010 GX₁₄ | 1.6E+17   | 29.9         | 1.2                    | -          | 1.6E+07 | -                           | -                           | -                              |
| 2010 JJ₁₂₄| 9.7E+17   | 54.8         | 2.1                    | -          | 4.6E+06 | -                           | -                           | -                              |
| 2010 PL₁₆₆| 1.9E+17   | 31.7         | 1.2                    | -          | 1.4E+07 | -                           | -                           | -                              |
| 2015 FZ₁₁₇| 8.0E+15   | 11.1         | 0.4                    | -          | 1.1E+08 | -                           | -                           | -                              |
Due to the lack of suitable spatial resolution by the current astronomical instrumentation binary systems in the typical distances of Centaurs cannot be discovered by direct imaging, but light curves with long rotation periods may be an indication for such systems. As shown for Centaurs in this paper and also previously for other small body populations (e.g. [Szabó et al., 2017] [Molnár et al., 2018]) long, uninterrupted time series photometry is usually necessary to fully characterise such systems. The K2 mission of the Kepler was an excellent tool for these kind of studies (see [Barentsen et al., 2018] for a summary). Similar results are expected from the TESS mission for Solar system targets [Pál et al., 2018].

Acknowledgements

The research leading to these results has received funding from the European Unions Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 687378; from the K-125015, PD-116175, PD-128360, and GINOP-2.3.2-15-2016-00003 grants of the National Research, Development and Innovation Office (NKFIH, Hungary); and from the LP2012-31 and LP2018-7/2019 Lendület grants of the Hungarian Academy of Sciences. L. M. was supported by the Premium Postdoctoral Research Program of the Hungarian Academy of Sciences. The research leading to these results have been supported by the UNKP-19-2 New National Excellence Program of the Ministry of Human Capacities, Hungary. Funding for the Kepler and K2 missions are provided by the NASA Science Mission Directorate. The data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. The authors thank the hospitality of the Veszprém Regional Centre of the Hungarian Academy of Sciences (MTA VEAB), where part of this project was carried out. We also indebted to S. Benecechi and an anonymous reviewer for their comments which have helped to improve the paper.

References

Alvarez-Candal, A., Pinilla-Alonso, N., Ortiz, J.-L., Duffard, R., Morales, N., Santos-Sanz, P., A. Thirouin, A., J. S. Silva, J.S., 2016, Absolute magnitudes and phase coefficients of trans-Neptunian objects, Astronomy & Astrophysics, 586, A155
Ayala-Leora, C., Alvarez-Candal, A., Ortiz, J.L., Duffard, R., Fernandez-Valenzuela, E., Santos-Sanz, P., Morales, N., 2018, Monthly Notices of the Royal Astronomical Society, 481, 1848–1857
Bailey, B.L. & Malhotra, R., 2009, Two dynamical classes of Centaurs, Icarus, Volume 203, Issue 1, 155-163.
Barentsen, G., Hedges, C., Saunders, N., et al., 2018, Kepler’s Discoveries Will Continue: 21 Important Scientific Opportunities with Kepler & K2 (white paper, arXiv:1810.12554)
Benecechi, S.D. & Sheppard, S.S., 2013, Light Curves of 32 Large Trans-Neptunian Objects, The Astronomical Journal, Volume 145, Issue 5, article id. 124
Benecechi, S.D.; Lisse, C.M.; Ryan, E.L.; Binzel, R.P.; Schwamb, M.E.; Young, L.A.; Verbiscer, A.J., 2018, K2 precision lightcurve: Twelve days in the Pluto-Charon system, Icarus, Volume 314, p. 265-273
Berthier, J., Carry, B., Vachier, F., Eggl, S., & Santerne, A., 2016, Prediction of transits of Solar system objects in Kepler/K2 images: an extension of the Virtual Observatory service SkyBoT, Monthly Notices of the Royal Astronomical Society, Volume 458, Issue 3, p.3394-3398
Davis, D.R., Farinella, P., 1997, Collisional Evolution of Edgeworth-Kuiper Belt Objects, Icarus, Volume 125, Issue 1, pp. 50-60
Di Sisto, R.P., & Brunini, A. 2007, The origin and distribution of the Centaur population, Icarus, Volume 190, Issue 1, p. 224-235.
Di Sisto, R.P., Brunini, A., de Elia, G.C., 2010, Dynamical evolution of escaped plutinos, another source of Centaurs, Astronomy and Astrophysics, Volume 519, id.A112, 7 pp.
Donnison, J.R., 2003, Statistical evidence for fast and slow asteroid rotations using Bayesian methods, Monthly Notice of the Royal Astronomical Society, Volume 338, Issue 2, pp. 452-456.
Dotto, E.; Perna, D.; Barucci, M. A.; Rossi, A.; de Bergh, C.; Doressoundiram, A.; Fornasier, S., 2008, Rotational properties of Centaurs and Trans-Neptunian Objects. Lightcurves and densities, Astronomy and Astrophysics, Volume 490, Issue 2, 2008, pp.829-833
Duffard, R., Ortiz, J.L., Thirouin, A., Santos-Sanz, P., Morales, N., 2009, Trans-neptunian objects and Centaurs from light curves, Astronomy and Astrophysics, Volume 505, Issue 3, 2009, pp.1283-1295
Duffard, R.; Pinilla-Alonso, N.; Santos-Sanz, P.; Vilenius, E.; Ortiz, J. L.; Mueller, T.; Fornasier, S.; Lellouch, E.; Momment, M.; Pal, A.; Kiss, C.; Mueller, M.; Stansberry, J.; Delsanti, A.; Peixinho, N.; Trilling, D. 2014, “TNOs are Cool”: A survey of the trans-Neptunian region. XI. A Herschel-PACS view of 16 Centaurs, Astronomy and Astrophysics, Volume 564, id.A92, 17 pp.
Elliot, J. L.; Kern, S. D.; Clancy, K. B.; Gultis, A. A. S.; Mills, R. L.; Buie, M. W.; Wasserman, L. H.; Chang, E. I.; Jordan, A. B.; Trilling, D. E.; Meech, K. J., 2005, The Deep Ecliptic Survey: A Search for Kuiper Belt Objects and Centaurs. II. Dynamical Classification, the Kuiper Belt Plane, and the Core Population, The Astronomical Journal, Volume 129, Issue 2, pp. 1117-1162
Farkas-Takács, A.; Kiss, Cs.; Pál, A.; Molnár, L.; Szabó, Gy. M.; Hanyecz, O.; Sárnéczky, K.; Szabó, R.; Marton, G.; Momment, M.; Szakáts, R.; Müller, T.; Kiss, L.L., 2017, Properties of the Irregular Satellite System around Uranus Inferred from K2, Herschel, and Spitzer Observations, The Astronomical Journal, Volume 154, Issue 3, article id. 119, 13 pp.
Noll, K.S., Grundy, W.M., Chiang, E.-I., Margot, J.-L., & S. D. Kern, S.D., Binaries in the Kuiper Belt, in: The Solar System Beyond Neptune, University of Arizona Press

Noll, Keith S.; Parker, Alex H.; Grundy, William M., 2014, All Bright Cold Classical KBOs are Binary, American Astronomical Society, DPS meeting #46, id.507.05

Ortiz, J.L., Gutiérrez, P.J., Casanova, V., & Sota, A., 2003, A study of short term rotational variability in TNOs and Centaurs from Sierra Nevada Observatory, Astronomy and Astrophysics, v.407, p.1149-1155

Ortiz, J.L., Gutiérrez, P.J., Santos-Sanz, P., Casanova, V., & Sota, A., 2006, Short-term rotational variability of eight KBOs from Sierra Nevada Observatory, Astronomy and Astrophysics, Volume 447, Issue 3, March I 2006, pp.1131-1144

Pál, A., 2012, FITSH – a software package for image processing, Monthly Notices of the Royal Astronomical Society, Volume 421, Issue 3, pp. 1825-1837.

Pál, A.; Szabó, R.; Szabó, Gy.M.; Kiss, L.L.; Molnár, L.; Sárneczky, K.; Kiss, Cs., 2015, Pushing the Limits: K2 Observations of the Trans-Neptonian Objects 2002 GV11 and (278361) 2007 JF131, The Astrophysical Journal Letters, Volume 804, Issue 2, article id. L45, 5 pp.

Pál, A.; Kiss, Cs., Horner, J.; Szakáts, R.; Vilenius, E.; Müller, Th. G.; Acasto-Pulido, J.; Licandro, J.; Cabrera-Lavés, A.; Sárneczky, K.; Szabó, Gy. M.; Throuan, A.; Szibócz, B.; Dózsa, A.; Duffard, R., 2015b, Physical properties of the extreme Centaur and super-comet candidate 2013 AZ10, Astronomy and Astrophysics, Volume 583, id.A93, 8 pp.

Pál, A., Kiss, C., Müller, T.G.; Molnár, L.; Szabó, R.; Szabó, G.M., Sárneczky, K.; Kiss, L.L., Large Size and Slow Rotation of the Trans-Neptunian Object (225088) 2007 OR₁₀ Discovered from Herschel and K2 Observations, The Astronomical Journal, Volume 151, Issue 5, article id. 117, 8 pp.

Pál, A., Molnár, L., Kiss, Cs., 2018, TESS in the Solar System, Publications of the Astronomical Society of the Pacific, Volume 130, Issue 993, pp. 114503

Peixinho, Nuno; Thirouin, Audrey; Tegler, Stephen C.; Di Sisto, Romina P.; Delsanti, Audrey; Guilbert-Lepoutre, Aurélie; Bauer, James G., 2020, ‘From Centaurs to comets – 40 years’ in ‘The Transneptunian Solar System’, eds.: D. Prialnik, M.A. Barucci, & L. Young, Elsevier, p.307-329

Porter, S.B., Grundy, W.M., 2012, KCTF evolution of trans-neptunian binaries: Connecting formation to observation, Icarus, Volume 220, Issue 2, p. 947-957

Pravec, P., Harris, A.W., 2000, Fast and Slow Rotation of Asteroids, Icarus, 148, p. 12–20

Pravec, P., Harris, A.W., 2007, Binary asteroid population. 1. Angular momentum content, Icarus, Volume 190, Issue 1, pp. 1-18

Pravec, P., Harris, A.W., 2000, Fast and Slow Rotation of Asteroids, Icarus, 148, p. 12–20

Pravec, P., Harris, A.W., Pravec, P., 2009, The asteroid lightcurve database, Icarus, Volume 202, Issue 1, p. 134-146, updated on 2019 August 60

Pérez, D., Grundy, W.M., 2014, All Bright Cold Classical KBOs are Binary, American Astronomical Society, DPS meeting #46, id.507.05

Ryan, E.L., Sharkley, B.N.L., Woodward, C.E., 2017, Trojan Asteroids in the Kepler Campaign 6 Field, The Astronomical Journal, Volume 153, Issue 3, article id. 116, 12 pp.

Sheppard, S.S., & Jewitt, D.C., The shapes, densities, and phase functions of trans-Neptunian objects, 2002, in Asteroids, Comets, and Meteors: ACM 2002, ed. B. Warmbein, ESA SP, 500, 21

Sheppard, S.S. & Jewitt, D.C., 2003, Earth Moon and Planets, 92, 207

Sheppard, S.S. & Jewitt, D., 2004, Extreme Kuiper Belt Object 2001 QG298 and the Fraction of Contact Binaries, The Astronomical Journal, Volume 127, Issue 5, pp. 3023-3033.

Sheppard, S. S., Lacerda, P., & Ortiz, J. L., 2008, Photometric Lightcurves of Transneptunian Objects and Centaurs: Rotations, Shapes, and Densities, in: The Solar System Beyond Neptune, University of Arizona Press

Szabó, R.; Sárneczky, K.; Szabó, Gy. M.; Pál, A.; Kiss, Cs.P.; Csák, B.; Illés, L.; Rácz, G.; Kiss, L. L., 2015, Main-belt Asteroids in the K2 Engineering Field of View, The Astronomical Journal, Volume 149, Issue 3, article id. 112, 5 pp.

Szabó, R.; Pál, A.; Sárneczky, K.; Szabó, Gy. M.; Molnár, L.; Kiss, L. L.; Hanyecz, O.; Plachy, E.; Kiss, Cs., 2016, Uninterrupted optical light curves of main-belt asteroids from the K2 mission, Astronomy and Astrophysics, Volume 596, id.A40, 9 pp.

Szabó, Gy.M.; Pál, A.; Kiss, Cs.; Kiss, L.L.; Molnár, L.; Hanyecz, O.; Plachy, E.; Sárneczky, K.; Szabó, R., 2017, The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids, Astronomy and Astrophysics, Volume 599, id.A44, 13 pp.

Taylor, P.A. & Margot, J.-L., 2011, Binary asteroid systems: Tidal end states and estimates of material properties, Icarus, 212, 661-676

Tegler, S.C., Romanishin, W., Consolmagno, G.J., 2016, Two Color Populations of Kuiper Belt and Centaur Objects and the Small Orbital Inclinations of Red Centaur Objects, The Astronomical Journal, Volume 152, Issue 6, article id. 210, 13 pp.

Thirouin, A., Ortiz, J. L., Duffard, R., Santos-Sanz, P., Aceituno, F. J., Morales, N., 2010, Short-term variability of a sample of 29 trans-Neptunian objects and Centaurs, Astronomy and Astrophysics, Volume 522, id.A93, 43 pp.

Thirouin, A., Sheppard, S.S., 2017, A Possible Dynamically Cold Classical Contact Binary: (126719) 2002 CC249, The Astronomical Journal, Volume 154, Issue 6, article id. 241, 8 pp.

Thirouin, A., Sheppard, S.S., Noll, K.S., 2017, 2004 TT₃₅: A Potential Contact Binary in the Trans-Neptunian Belt, The Astrophysical Journal, Volume 844, Issue 2, article id. 115, 6 pp.

Thirouin, A., Sheppard, S.S., 2018, The Plutino Population: An Abundance of Contact Binaries, The Astronomical Journal, Volume 155, Issue 6, article id. 248, 16 pp.

Thirouin, A., Sheppard, S.S., 2019, Light Curves and Rotational Properties of the Pristine Cold Classical Kuiper Belt Objects, The Astronomical Journal, Volume 157, Issue 6, article id. 228, 19 pp.

Tiscareno, M. S. & Malhotra, R., 2003, The Dynamics of Known Centaurs, The Astronomical Journal, Volume 126, Issue 6, pp. 3122-3131.

Vilenius, E.; Kiss, C.; Müller, T.; Mommer, M.; Santos-Sanz, P.; Pál, A.; Stansbery, J.; Mueller, M.; Peixinho, N.; Lellouch, E.; Fornasier, S.; Delsanti, A.; Thirouin, A.; Ortiz, J. L.; Duffard, R.; Perina, D.; Henry, F., 2014, "TNOs are Cool": A survey of the trans-Neptunian region. X. Analysis of classical Kuiper belt objects from Herschel and Spitzer observations, Astronomy & Astrophysics, Volume 564, id.A35, 18 pp.

Warner, B.D., Harris, A.W., Pravec, P., 2009, The asteroid lightcurve database, Icarus, Volume 202 Issue 1, p. 134-146, updated on 2019 August 14, http://www.MinorPlanet.info/lightcurvedatabase.html

16
Wlodarczyk, I., Cernis, K., & Boyle, R.P., 2017, Discovery, Orbit and Orbital Evolution of the Distant Object (463368) 2012 VU85, Acta Astronomica, 67, 81
Wong, Ian; Mishra, Aakash; Brown, Michael E., 2019, Photometry of Active Centaurs: Colors of Dormant Active Centaur Nuclei, The Astronomical Journal, Volume 157, Issue 6, article id. 225, 11 pp.
Zima, W., 2008, FAMIAS - A user friendly new software tool for the mode identification of photometric and spectroscopic times series, Communications in Asteroseismology, Vol.157, p. 387