PUSHING THE LIMITS: K2 OBSERVATIONS OF THE TRANS-NEPTUNIAN OBJECTS
2002 GV$_{31}$ and (278361) 2007 JJ$_{43}$

A. Pál$^{1,2}$, R. Szabó$^3$, GY. M. Szabó$^{5,3,4}$, L. L. Kiss$^{1,4,5}$, L. Molnár$^1$, K. Sárnéczky$^{1,4}$, and Cs. Kiss$^1$

$^1$Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út 15-17, Hungary; apal@szof.net
$^2$Loránd Eötvös University, H-1117 Pázmány Péter sétány 1/A, Budapest, Hungary
$^3$ELTE Gothard Astrophysical Observatory, H-9704 Szombathely, Szent Imre herceg út 112, Hungary
$^4$Goddard-Lendület Research Team, H-9704 Szombathely, Szent Imre herceg út 112, Hungary
$^5$Sydney Institute for Astronomy, School of Physics A28, University of Sydney, Sydney, NSW 2006, Australia

Received 2015 March 30; accepted 2015 April 14; published 2015 May 12

ABSTRACT

We present the first photometric observations of trans-Neptunian objects (TNOs) taken with the Kepler space telescope, obtained during the course of the K2 ecliptic survey. Two faint objects have been monitored in specifically designed pixel masks that were centered on the stationary points of the objects, when their daily motion was the slowest. In the design of the experiment, only the apparent path of these objects were retrieved from the detectors, i.e., the costs in terms of Kepler pixels were minimized. Because of the faintness of the targets, we employ specific reduction techniques and co-added images. We measure rotational periods and amplitudes in the unfiltered Kepler band as follows: for (278361) 2007 JJ$_{43}$ and 2002 GV$_{31}$, we get $P_{\text{rot}} = 12.097 \text{ hr}$ and $P_{\text{rot}} = 29.2$ hr with 0.10 and 0.35 mag for the total amplitudes, respectively. Future space missions, such as TESS and PLATO, are not well suited to this kind of observation. Therefore, we encourage including the brightest TNOs around their stationary points in each observing campaign to exploit this unique capability of the K2 Mission—and therefore to provide unbiased rotational, shape, and albedo characteristics of many objects.

Key words: astrometry – Kuiper belt objects: individual (2002 GV$_{31}$, 2007 JJ$_{43}$) – methods: observational – minor planets, asteroids: general – techniques: photometric

Supporting material: machine-readable table

1. INTRODUCTION

Kepler has provided incredible results on extrasolar planets and planetary systems, as well as on stellar astrophysics. After analyzing main-belt asteroids (Szabó et al. 2015), here we continue the exploration of our own solar system by pushing the limits of the spacecraft and observing faint, trans-Neptunian objects (TNOs).

The Kepler spacecraft is equipped with a 0.95 m Schmidt telescope and 42 imaging CCDs, of which 38 are currently in operation. Kepler was designed to be the most precise photometer in order to detect the transits of numerous small planets (Borucki et al. 2010). It monitored approximately 170,000 targets in the Lyra–Cygnus field, at high ecliptic latitudes, almost continuously for four years during its primary mission. However, after the failure of two reaction wheels, the telescope permanently lost its ability to maintain that attitude. Shortly thereafter, a new mission, called K2, was initiated to save the otherwise healthy and capable space telescope (Howell et al. 2014). Since then, Kepler has been observing in shorter, 75 day long campaigns along the ecliptic to balance the radiation pressure from the Sun.

The ecliptic fields include innumerable solar system objects, although most asteroids and planets cross the field of view quite quickly. TNOs, in contrast, appear to move slowly around their stationary points and can be observed for extended periods of time. The 4″ pixel resolution of the CCDs is sufficient to avoid confusion, even for faint targets. However, the observations posed various challenges for Kepler. Even the brighter TNOs are at the detection limit of the telescope ($V = 20–22 \text{ mag}$), with an expected precision of a few tenths of a magnitude for a single long-cadence (30 minute) observation. Moreover, TNOs exhibit quadratically increasing proper motions away from the stationary points. Since the pixel mask allocation is fixed for an entire campaign, the whole length of the orbital arc has to be observed continuously. Despite these challenges, the K2 mission is in a unique position to gather continuous TNO light curves in white light.

The rotational light curve of small bodies in the solar system is determined by the shape and albedo variegations on the surface of the target and provides information on these important characteristics. In addition, the collisional history of these bodies is stored in the spin state of the objects, probing different eras of the solar system’s debris disk evolution depending on the size. The largest objects (~500 km or larger in diameter) decoupled early from collisional evolution of the debris disks; therefore, their rotation should reflect the cumulative effect of collisions during the formation period. Medium size objects (100–500 km) likely avoided catastrophic impacts with a rotation affected by smaller past events, while the smallest bodies (<100 km) are probably remnants of several collisions during the evolution of the solar system’s debris disk (for more details, see also Lacerda 2005).

In order to study the rotational properties of TNOs, we proposed a pilot study for the K2 Campaign 1 to observe the object 2002 GV$_{31}$ ($V \approx 22.5 \text{ mag}$) with a small pixel mask for a limited time around the stationary point (proposal ID GO1064). The field of Campaign 2 included multiple moderately bright targets from which ultimately only (278361) 2007 JJ$_{43}$ ($V \approx 20.25 \text{ mag}$) was selected for observation (proposal IDs GO2066 and GO3053).
2. OBSERVATIONS

For 2002 GV$_{31}$, a rectangular, $23 \times 22$ pixel mask was allocated by the Guest Observer Office that included the object for 16 days around its stationary point, but 2.8 days were lost to a mid-campaign data download period. In contrast, 2007 JJ$_{43}$ was covered with a long arc constructed from a mosaic of 661 small ($1 \times 11$ or $1 \times 13$) pixel masks, but the region of the stationary point itself fell off silicon. This caused a 20.9 day long gap in the observations, separating the data into a 18.7 day and a 39.2 day long section.

The elongation of the object decreased from $135^{\circ}$ to $60^{\circ}$ during the campaign. The public target pixel time series files from the C1 and C2 fields were retrieved from the MAST archive for the respective observations.

Without stabilization around the third axis, the Kepler space telescope slowly rolls about the optical axis. This movement causes the field of view to rotate slightly, and it is corrected by the on-board thrusters at every 5.88 hr ($f_{\text{corr}} = 4.08 \text{ days}^{-1}$). The spacecraft stores the pixels of pre-selected targets only, similar to the primary mission, but larger target pixel masks are allocated for fewer targets in the K2 fields to accommodate the larger pointing jitter and less frequent data download periods. Hence, the data acquisition principles are similar to the stellar targets, only the combination of the small pixel masks of 2007 JJ$_{43}$ required additional steps during analysis.

The attitude of the spacecraft was adjusted by a few pixels shortly after the start of both campaigns. This did not affect the data of 2002 GV$_{31}$, but in the first 49 frames of Campaign 2, 2007 JJ$_{43}$ was too close to the edge of the mask and those were discarded. Apart from these adjustments, the largest correction movements were always smaller than a pixel, and the rms of the image shift offsets was 0.3 pixels for both campaigns. A closer inspection of the field-of-view movements revealed that the direction of motion reversed at the middle of the campaign, and in some cases, the correction maneuver did not occur, and the telescope drifted for 11.76 hr (instead of 5.88 hr).

3. DATA REDUCTION

While the target pixel file contained a single stamp of $23 \times 22$ pixels in the case of 2002 GV$_{31}$, the data extraction was much more complex in the case of 2007 JJ$_{43}$. Here, the total mask related to this object has been split into individual target stamps containing only $1 \times 11$ or $1 \times 13$ pixels. Hence, the first step of the reduction was the reconstruction of the effective section of the target CCD areas and the marking of the outlier pixels (in order to exclude them from further data processing). In the case of 2002 GV$_{31}$, we employed the PyKE package (Still & Barclay 2012) to create individual FITS frames for each timestamp, while the combined and marked frame series for 2007 JJ$_{43}$ was created using the utilities of the FITSH package (Pál 2012). Prior to the light curve analysis (see Section 4), for the subsequent data processing steps, we employed various tasks of the FITSH package (especially sigm, fitrans, grtrans, grmatch, fiphot, and fistar).

Since the target pixel time series does not contain information regarding the time variation of the astrometric solutions of the individual smaller stamps, frame registration had to be based purely on imaging data. Due to the fairly strange shape of the field containing the apparent path of 2007 JJ$_{43}$ (see Figure 1), automatic source identification and cross-matching algorithms based on triangulation matching (see also Pál & Bakos 2006) were not found to be effective. Therefore, we manually selected seven prominent stars distributed nearly uniformly in the field. Namely, we picked four stars located in the northern stripe and three stars in the southern stripe. Initial pixel coordinates for these stars have been acquired using the imexam tool of IRAF on adjacent frame pairs belonging to events where the pointing of Kepler was changed abruptly. We found that this kind of manual analysis of 39 images was sufficient in order to bootstrap the astrometry and for the cross-identification procedure for all of the 3789 individual images.

Photometry of 2007 JJ$_{43}$ was then performed using differential images (difference between the individual images and the aforementioned master image) where the aperture centered coordinates were based on Kepler-centric apparent positions retrieved from the NASA/Horizons service. The instrumental aperture was chosen to be relatively small due to the faintness of the object. Despite the usage of differential images, the residual structures were significant due to the undersampled property of the Kepler camera. Namely, the spline-based interpolation throughout the registration process always introduces undershootings in case of stellar profiles with small FWHMs yielding characteristic features on the residual images (see, e.g., Figure 4 in Pál 2009). Photometric uncertainties have been estimated considering photon noise and measured background scatter in the aperture annuli. For the photon noise estimation, we used the gain values reported in the original FITS header, namely, $113.3 \, e^\text{/ADU}$. As we will discuss later on (Section 4), this estimation was found to be reliable.

In the case of 2002 GV$_{31}$, we followed a similar data flow for image reduction, with the exception of the frame registration being much easier due to the smaller size and fewer number of stars (Figure 2). Namely, the number of unambiguously identified background stars was three, and the mean of the centroid shifts (in both directions) was used to obtain the offset values for the image registration. In addition, we binned the images into intervals of 0.1 days in order to increase the signal in the frames. Hence, each frame on which photometry is performed was derived from approximately five individual downlinked measurements. In all other aspects, the photometry was performed identically for the two objects.

For both objects, photometric magnitudes have been transformed into the USNO-B1.0 $R$ system (Monet et al. 2003).
In the case of 2007 JJ43, we found that the unbiased residuals of the photometric transformation between USNO and Kepler unfilled magnitudes was 0.05 mag, while for 2002 GV31 it was found to be 0.09 mag. Stars used for both objects have magnitudes spanning nearly homogeneously between ≈R15 and ≈R19. Photometric data are displayed in Table 1.

4. LIGHT CURVE ANALYSIS

The data produced from the baseline photometry consisted of time instance, magnitude, and magnitude errors; 2224 data points belonged to 2007 JJ43, and 129 points to 2002 GV31, respectively. We tested that the photometric error estimates by the reduction pipeline are quite realistic. The mean determined photometric error of the entire data set is 0.163 magnitudes, while the mean of the standard deviation of data points in the boxcar is 0.127 magnitudes. These values are comparable to each other within 30% accuracy. For later processing, the weights of the photometric data were set to be proportional to 

\[ \sigma_i^2 \]

where \( \sigma_i \) is the formal photometric error of each data point.

We also observed that this approach overweighted the outliers on the bright side and may introduce a distortion in the shape of the light curve. This is because error sources, such as residuals after image subtraction, scatter toward both directions (too faint and too bright), but the mean brightness is biased here because the formal errors of bright-looking objects are much smaller, and they are given larger weights. Therefore, at the bright wing of data distribution, the weights were downscaled by a function of the shape

\[ \arctan(8 e^{-d^2/\sigma^2}) + 0.3, \]

where \( d = m - m_0 \), the deviation of the measured \( m \) magnitudes from the mean value. We selected \( \mu \approx 4 \) times the peak of the Fourier spectrum at the rotational period (0.15 for 2007 JJ43 and 0.5 for 2002 GV31, respectively). Here, the peak of the Gaussian curve is damped by the \( \arctan(\cdot) \) function acting on it, leading to a flat plateau around the center of the shape. We are convinced that this rescaling leads to more realistic weights than the crude estimates making use of the measured flux values. However, in order to avoid biasing the results in any way, we compared the results with and without weighting, and we experienced that they were practically equal.

### Table 1

| Object    | Time (JD)         | Magnitudea | Error  |
|-----------|-------------------|------------|--------|
| 2007 JJ43 | 2456893.044947    | 20.288     | 0.078  |
|           | 2456893.208405    | 20.686     | 0.111  |
|           | 2456893.228837    | 20.722     | 0.105  |
| 2002 GV31 | 2456839.65        | 23.680     | 0.606  |
|           | 2456839.75        | 22.862     | 0.402  |
|           | 2456839.85        | 22.957     | 0.403  |

a Magnitudes shown here are transformed to the USNO-B1.0 R system (see the text for further details).

(This table is available in its entirety in machine-readable form.)
identical—so the modified weights merely supported the better visualization.

The rotation periods were found by a Fourier analysis. The Fourier transform of the light curves was calculated by the Period04 code (Lenz & Breger 2005). To exclude the light variation introduced by periodic systematics, we also calculated the periodograms of the pointing position of the telescope, the actual and the measured subpixel positions of the TNOs in each frames. We did not find periodic signals resulting from the sampling effects (therefore, subpixel positions), but we identified the peak due to the pointing corrections with 4.05 cycle days⁻¹ frequency (Figure 3). This is close to the frequency peak belonging to a half rotation of 2007 JJ₄₃, but they are still well separated, proving that the periodograms of the TNOs reflect the rotation.

5. RESULTS

5.1. (278361) 2007 JJ₄₃

(278361) 2007 JJ₄₃ is an outer Kuiper belt object, likely in 2:1 resonance with Neptune (MPC 2007). Based on its absolute magnitude at discovery (Hᵥ = 3.9) and the cluster average geometric albedo of pᵥ = 0.13 ± 0.09 for objects in the outer Kuiper belt (Lacerda et al. 2014), its likely effective diameter is Dₑᵥ = 610 ± 170 km. 2007 JJ₄₃ was also detected by the Southern sky and galactic plane survey for bright Kuiper belt objects (Sheppard et al. 2011), and an R-band absolute magnitude of Hᵣ = 3.2 was associated with the object.

Benecchi & Sheppard (2013) detected a light curve of 2007 JJ₄₃, with a peak-to-peak amplitude of 0.13 ± 0.02 in the Sloan r' band. The most likely light curve (rotation) period they found was 6.04 hr or, just as likely, its double period, 12.09 hr. However, other periods (4.83/9.66 hr) were also possible. The light curve was clearly non-sinusoidal. The absolute magnitude in this band was found to be Hᵣ = 4.17 ± 0.20.

The period analysis confirmed the most likely solution of Benecchi & Sheppard (2013), namely, 6.048 ± 0.018 hr. This is clearly the half of the rotation period confirmed by the asymmetry of the phased light curve with the P = 12.097 ± 0.036 hr period (left panel of Figure 4). Weighted means of the magnitude and corresponding phases were calculated in a boxcar of 68 data points. The standard deviation and the number of points in each bin resulted in an expected standard deviation (error bars) of ≈0.015 magnitudes for the binned points. The smoothed light curve shows two humps with equivalent minima and slightly different peaks. The full amplitude is 0.100 ± 0.005 magnitude; the difference between the minima is 0.02 magnitudes. The asymmetry and the non-sinusoidal shape of the light curve reflect the uneven surface structures. These features are quite common for solar system objects, e.g., a very similar light curve shape is observed for the main-belt asteroid (52) Europa at certain observing circumstances (e.g., Michalowski et al. 2004). We can also conclude that the presented K2 measurement and the photometry of 2007 JJ₄₃ in Benecchi & Sheppard (2013) show similar characteristics since in the case of TNOs, the phase, and aspect angles vary rather slowly on the timescale of these observations.

5.2. 2002 GV₃₁

2002 GV₃₁ is a dynamically cold classical Kuiper belt object. A recent evaluation of Johnson R-band MPC data and a conversion using V−R = 0.59 ± 0.15 (average for classicals) resulted in a V-band absolute magnitude of Hᵥ = 6.1 ± 0.6. 2002 GV₃₁ was observed, but not detected, in any bands of the PACS camera on board the Herschel Space Observatory in the framework of the “TNOs are Cool!” Open Time Key Program (Müller et al. 2009). Using the upper limits set by the nondetections, a modeling of the thermal emission of the target resulted in an upper limit of its size (D < 180 km) and a lower limit on its geometric albedo (0.19 < pᵥ; see Vilenius et al. 2012, 2014). No light curve information is available for this target.
The first light curve of this object is shown in the right panel of Figure 4, phased with the most likely rotation period of 29.2 ± 1.1 hr and showing a double peak. Since we had 129 photometric points from K2 in this case, they were binned into 13 points during one rotation, and the error bar of the binned points was found to be 0.06 magnitudes. The full amplitude of the light variation is 0.35 magnitudes, which can be a sign of a more exposed asphericity than for 2007 JJ43. The most interesting feature of this TNO is its long rotation period, as most TNOs and Centaurs have rotation periods shorter than a day (Duffard et al. 2009; Benecchi & Sheppard 2013).

Longer periods are expected from synchronously locked, tidally evolved binary systems (see Pluto/Charon or Sila/Nunam; Grundy et al. 2012). It can explain the slow rotation of 2010 WG9 (Rabinowitz et al. 2013) and also can be a plausible explanation for 2002 GV31. Moreover, observational statistics can explain binarity, which is more likely for dynamically cold TNOs (Noll et al. 2008). In addition, statistics seem to prefer close orbits (Figure 4 in Noll et al. 2008), which can also yield mutual events and hence strong light curve variations.

6. CONCLUSIONS

We clearly detected the rotational signal of two TNOs with Kepler during the K2 extended ecliptic survey mission. Since these objects are moving through the field of view, photometric data reduction requires special care in order to retrieve accurate flux information. Although the image processing requires complex steps, our results clearly show that the moving nature of these targets is also advantageous. Namely, differential photometric techniques strenuously reduce the effects of background sources, even in the crowded Kepler fields and in the case of lower imaging resolution and undersampled stellar profiles. In addition, the employment of moving apertures removes the frequency aliases caused by the pointing corrections of the spacecraft every ~6 hr.

All in all, we successfully demonstrated that it is feasible to observe faint TNOs around their stationary points with Kepler! K2, and this mission provides a unique way to monitor them continuously for many weeks. The scientific benefit of observing TNOs is the opportunity to provide an unbiased sample of rotational light curves—and hence data about shape, albedo, and surface characteristics. This kind of information aids us in understanding the nature and evolution of the outer solar system.

Future space missions, such as TESS and PLATO, are not well suited to this kind of observation; therefore, we encourage including the brightest TNOs in each observing campaign to exploit this unique capability of the K2 Mission.

We thank the hospitality of the Veszpréms Regional Centre of the Hungarian Academy of Sciences (MTA VEAB), where most of our work was carried out. We also thank the anonymous referee for comments. This project has been supported by the Lendület-2009 and LP2012-31 Young Researchers Programs; the Hungarian OTKA grants K-38790, K-109276, and K-104607; and the City of Szombathely under agreement No. S-11-1027. The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007–2013) under grant agreements Nos. 269194 (IRSES/ASK) and 312844 (SPACEINN), and the ESA PECS contract Nos. 4000110889/14/NL/ND and 4000109997/13/NL/KML. Gy.M.S. and Cs.K. were supported by the János Bolyai Research Scholarship. Funding for the K2 mission is provided by the NASA Science Mission directorate. The authors acknowledge the Kepler team for the extra efforts to allocate special pixel masks to track moving targets. All of 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-Hubble Space Telescope data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts.

REFERENCES

Benecchi, S. D., & Sheppard, S. S. 2013, AJ, 145, 124
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Duffard, R., Ortiz, J. L., Thirouin, A., Santos-Sanz, P., & Morales, N. 2009, A&A, 505, 1283
Grundy, W. M., Benecchi, S. D., Rabinowitz, D. L., et al. 2012, Icar, 220, 74
Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 598
Lacerda, P. 2005, Phd thesis, Leiden Univ.
Lacerda, P., Fornasier, S., Lellouch, E., et al. 2014, ApJL, 793, 2
Lenz, P., & Breger, M. 2005, CoAst, 146, 53
MPC 2007, Minor Planet Circulards 60235 (Cambridge, MA: Minor Planet Center)
Michalowski, T., Kwiatkowski, T., Kaasalainen, M., et al. 2004, A&A, 416, 353
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Müller, T. G., Lellouch, E., Bönhardt, H., et al. 2009, EM&P, 105, 209
Noll, K. S., Grundy, W. M., Chiang, E. I., Margot, J.-L., & Kern, S. D. 2008, in The Solar System Beyond Neptune ed. A. Barucci et al. (Tucson: Univ. Arizona Press)
Pál, A. 2009, PhD thesis, Eötvös Loránd Univ., Budapest, Hungary
Pál, A. 2012, MNRAS, 421, 1825
Pál, A., & Bakos, G. Á 2006, PASP, 118, 1474
Rabinowitz, D., Schwamb, M. E., Hadjiyska., E., Tourtellotte, S., & Rojo, P. 2013, AJ, 146, 17
Sheppard, S. S., Udalski, A., Trujillo, C., et al. 2011, AJ, 142, 98
Still, M., & Barclay, T. 2012, ascl, record ascl:1208.004
Szabó, R., Sárnezcky, K., Szabó, Gy. M., et al. 2015, AJ, 149, 112
Vilenius, E., Kiss, C., Momert, M., et al. 2012, A&A, 541, 94
Vilenius, E., Kiss, C., Müller, T., et al. 2014, A&A, 564, 35