

# Transit timing variations and linear ephemerides of confirmed *Kepler* transiting exoplanets

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**Abstract** We determine new linear ephemerides of transiting exoplanets using long-cadence de-trended data from quarters Q1 to Q17 of the *Kepler* mission. We analysed transit-timing variation (TTV) diagrams of 2098 extrasolar planets. The TTVs of 121 objects were excluded (because of insufficient datapoints, influence of stellar activity, etc.). Finally, new linear ephemerides of 1977 exoplanets from the *Kepler* archive are presented. A significant linear trend was observed on TTV diagrams of approximately 35% of the exoplanets studied. Knowing the correct linear ephemeris is key for successful follow-up observations of transits. Residual TTV diagrams of 64 analysed exoplanets show periodic variation, and 43 of these TTV planets were not previously reported.

**Key words:** stars: planetary systems — eclipses — techniques: photometric

## 1 INTRODUCTION

The *Kepler* satellite, launched in 2009, provided high-precision, high-cadence and continuous photometric data during its primary mission (Borucki et al. 2010). After losing two reaction wheels in 2013, the so-called *K2* mission started and still continues (Howell et al. 2014).

During its primary mission, *Kepler* discovered 2327 extrasolar planets (up to 2018 May 31). Almost half of them (1125) are located in 447 multi-planet systems. The final catalogue (DR25) of *Kepler* planet candidates was released in 2017 (Thompson et al. 2018). It consists of more than four thousand planet candidates.

In many of the known exoplanets, the variations in times of transits have already been observed. Holczer et al. (2016) detected 260 planet candidates with significant long-term variations. These variations could be caused by gravitational interaction with other bodies in the system. For example, Steffen et al. (2012) determined the masses of planets in the systems Kepler-25, Kepler-26, Kepler-27 and Kepler-28 using transit timing. A similar method has also been used to confirm the planets in multi-planetary systems (e.g. Fabrycky et al. (2012)). Many planet pairs are locked in mean motion resonances (MMRs) (Wang &

Ji 2017). The MMRs of 3:2 and 2:1 are the most common (Wang & Ji 2014).

## 2 LINEAR EPHEMERIS DETERMINATION

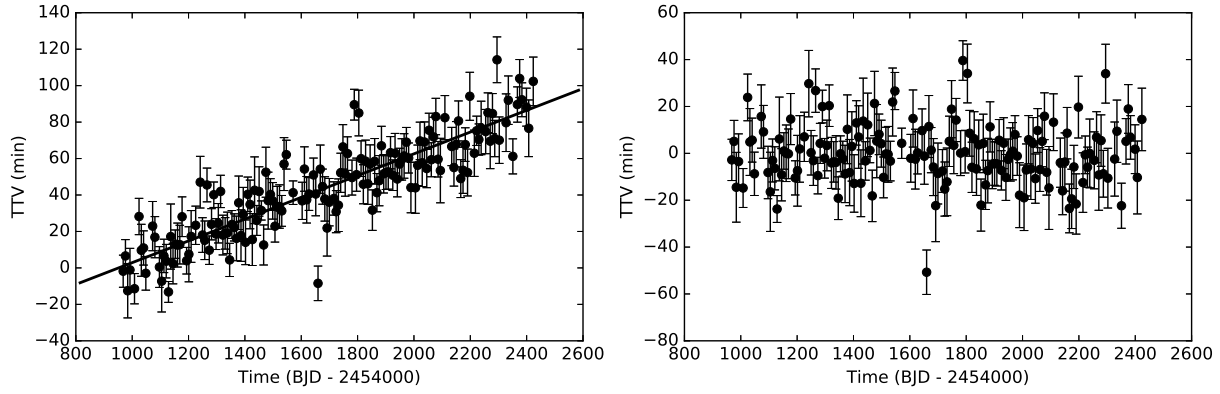
In our analysis, we considered long-cadence (sampled every 29.4 min) de-trended data (PDCSAP\_FLUX) from quarters Q1 to Q17 of the *Kepler* mission, obtained from the Mikulski Archive for Space Telescopes (MAST)<sup>1</sup>. To analyse the data, we relied on the same pipeline as in our study of transit-timing variations (TTVs) in the system Kepler-410 (Gajdoš et al. 2017). We used the same approach for all the planets we examined and obtained a homogeneous set of times of transits using one method. This process can be summarised in the following steps:

- (1) Parts of the light curve (LC) of the individual system were extracted around detected transits (using the ephemeris given by the NASA Exoplanet Archive<sup>2</sup> (Akeson et al. 2013)), with an interval two times bigger than the transit duration.

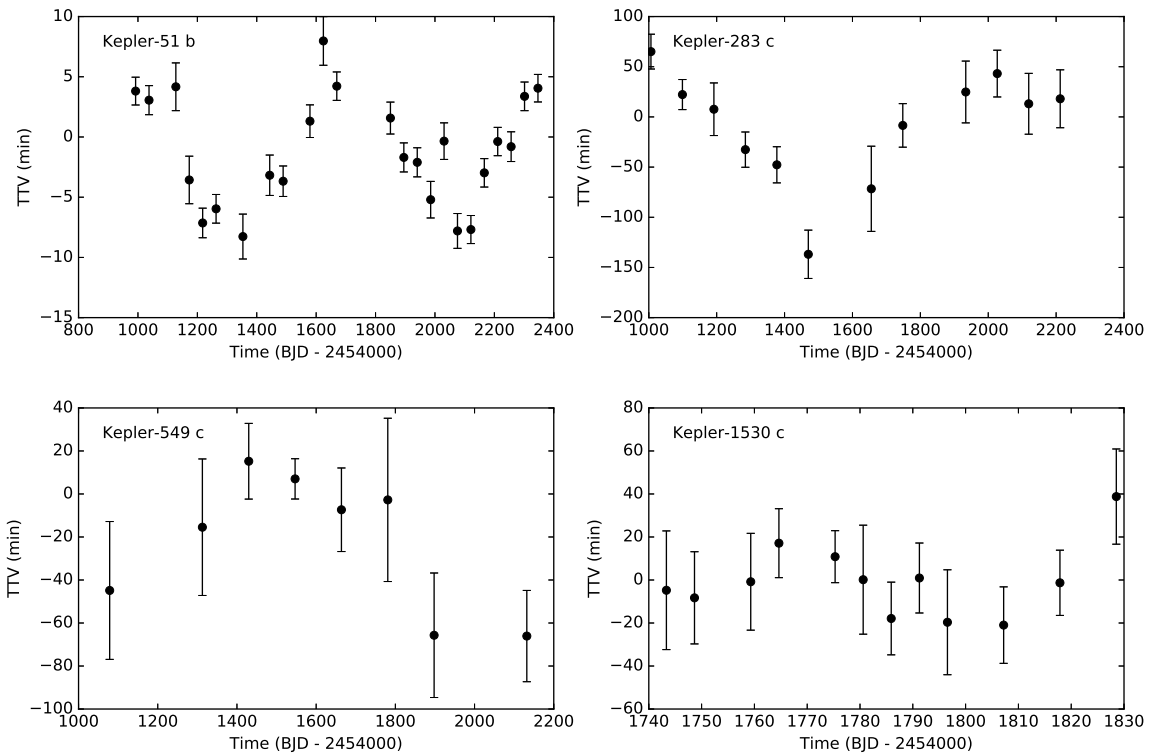
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<sup>2</sup> We used the Confirmed Planets table available at <https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=planets> Downloaded in April 2018.



**Fig. 1** *Left* – TTV of Kepler-114 c determined from the original ephemeris from the NASA Exoplanet Archive with a new linear fit (*solid line*), *Right* – residual TTV of Kepler-114 c (see note 1 in Table 1).



**Fig. 2** Examples of planets with periodic variations on the residual TTV diagram (note 2 in Table 1). Periods and amplitudes of these changes are listed in Tables 2 and 3.

- (2) Additional residual trends caused by stellar activity and/or instrumental long-term photometric variation were removed by fitting the out-of-transit part of the LC by a second-order polynomial function.
- (3) All individual parts of the LC with transits were stacked together. This can be done because one expects that the physical parameters of the host star and the exoplanet did not change during the observational

period of about 3.5 yr and we want to cancel out the effect of stellar activity.

- (4) The stacked LC was fitted by our software implementation of the Mandel & Agol (2002) model in which we used a quadratic model of limb darkening with values of coefficients from Sing (2010). Our package employs a Markov Chain Monte Carlo (MCMC) simulation to obtain statistically significant values of parameters and their errors.

**Table 1** The New Linear Ephemerides of *Kepler* Exoplanets

Name			New ephemeris		Fit statistics			Note
Common name	KOI	KIC	$P$ (d)	$T_0$ (BJD)	$\chi^2$	$\chi^2/n$	$n$	
Kepler-4 b	7.01	11853905	3.213663(1)	2454956.61167(24)	523.9	1.6	330	1
Kepler-5 b	18.01	8191672	3.5484659(1)	2454955.90135(3)	6020.5	16.0	379	1
Kepler-6 b	17.01	10874614	3.2346994(8)	2454954.48659(2)	5598.0	16.8	335	1
...	...	...	...	...	...	...	...	...
Kepler-1646 b	6863.01	7350067	4.485563(2)	2454968.43834(30)	9126.425	31.579	291	1

Notes: Common name, Kepler Object of Interest (KOI) and Kepler Input Catalog (KIC) - name of exoplanet,  $P$  - orbital period,  $T_0$  - an initial time of transit (uncertainties are given in parentheses),  $\chi^2$  - sum of squares of the best fit,  $\chi^2/n$  - reduced sum of squares,  $n$  - number of data points in TTV diagram, note - changes in residual TTV after new ephemeris is removed: 1 - no significant changes, 2 - periodic or quasi-periodic variations, 3 - chaotic variations (see text for a detailed description). The entire table is available as online material at <http://www.raa-journal.org/docs/Supp/ms4253tab1.txt>.

**Table 2** Comparison of periods and amplitudes of TTV changes found in this paper with values given by Holczer et al. (2016).

Name			Holczer et al. (2016)		This paper	
Common name	KOI	KIC	$P$ (d)	$A$ (m)	$P$ (d)	$A$ (m)
Kepler-25 b	244.02	4349452	326(3)	3.8(3)	334(2)	4.3(3)
Kepler-51 b	620.01	11773022	790(12)	7.9(4)	749(17)	5.5(5)
Kepler-81 c	877.02	7287995	536(12)	9(2)	516(9)	10(1)
Kepler-111 c	139.01	8559644	2213(79)	211(22)	1050(20)	38(2)
Kepler-139 c	316.02	8008067	1008(84)	29(8)	913(30)	35(3)
Kepler-209 c	672.02	7115785	1061(76)	9(2)	1141(63)	10(1)
Kepler-221 e	720.03	9963524	—	~9	1697(115)	11(1)
Kepler-278 c	1221.02	3640905	829(41)	144(32)	960(69)	112(16)
Kepler-312 c	1628.01	6975129	471(17)	6(2)	478(14)	7(1)
Kepler-359 c	2092.01	6696580	1270(130)	23(6)	1246(125)	20(6)
Kepler-540 b	374.01	8686097	1388(84)	38(6)	1457(54)	37(4)
Kepler-561 b	464.01	8890783	482(11)	3.9(6)	480(12)	4.1(7)
Kepler-591 b	536.01	10965008	454(37)	6(4)	579(35)	9(2)
Kepler-765 b	1086.01	10122255	1630(150)	20(4)	1445(133)	37(3)
Kepler-827 b	1355.01	7211141	124(1)	6(2)	398(36)	6(1)
Kepler-1040 b	1989.01	10779233	—	~15	901(30)	17(4)
Kepler-1624 b	4928.01	1873513	110(1)	2.1(7)	118(3)	1.9(2)

Notes: Common name, KOI and KIC - name of exoplanet,  $P$  - period of variation,  $A$  - amplitude (uncertainties are given in parentheses).

- (5) The obtained template was applied to fit all individual transits, where only the time of transit was updated.
- (6) The times of transits determined were used to create a TTV diagram of the object. It was subsequently fitted by a linear function to obtain new values of linear ephemeris parameters, initial time of transit  $T_0$  and orbital period  $P$ . To achieve a statistically significant estimation of parameter uncertainties, we executed an MCMC simulation. To estimate the quality of the statistical model, we calculated the  $\chi^2$  error and reduced  $\chi^2/n$  where  $n$  is the number of data points in the TTV diagram.
- (7) Finally, the new linear trend determined by the new ephemeris was removed and the residual TTV was visually inspected for other changes.

### 3 DISCUSSION AND CONCLUSIONS

We started our analysis of TTV diagrams with 2098 extra-solar planets from the *Kepler* database. We excluded 121 objects with TTV diagrams consisting of fewer than four points or with diagrams strongly affected by stellar activity. New linear ephemerides were determined for 1977 exoplanets. They are all presented in Table 1.

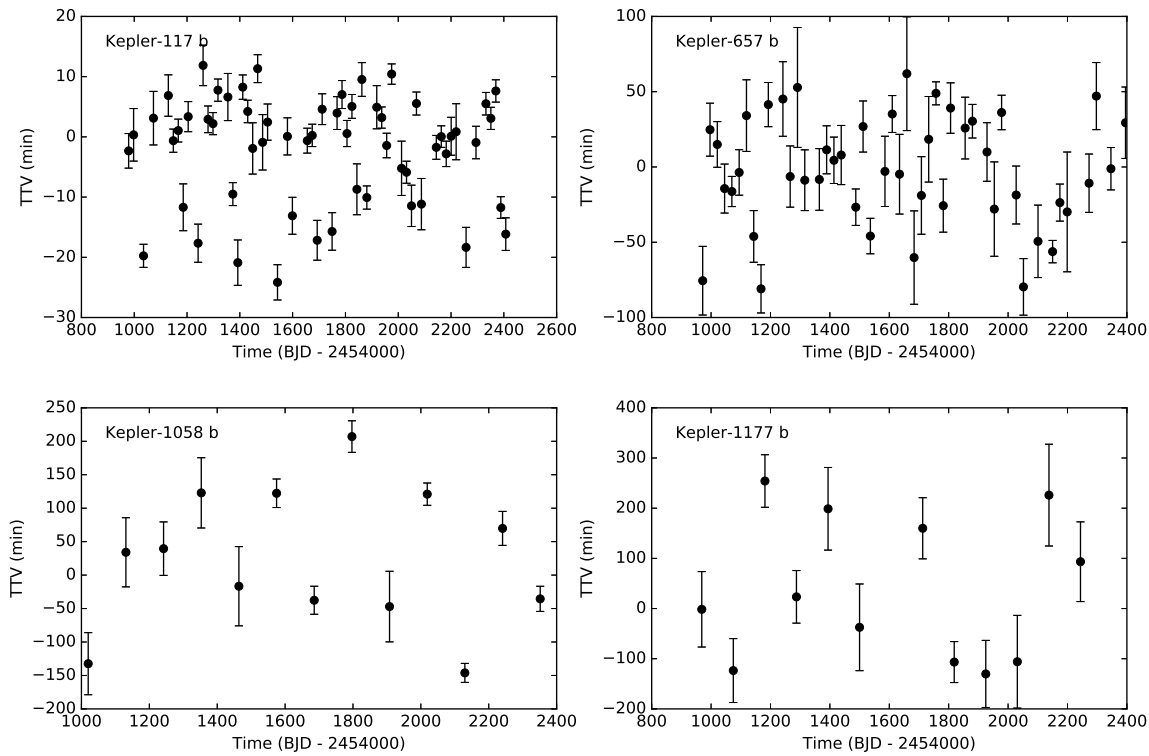
Our analysis revealed that in many cases ( $\sim 35\%$ ), a linear trend could be observed in the TTV diagrams which were calculated according to the original ephemerides given by the NASA Exoplanet Archive. Cumulative shift in the minima times of studied exoplanets can reach up to  $\sim 130$  min (e.g. Kepler-4 b) over 3.5 yr of *Kepler* observations. The example of such a significant trend detected in the system Kepler-114 c is shown in Figure 1 (left). The period of Kepler-114 c given by the NASA Exoplanet

**Table 3** Planets with periodic variations in TTV diagram not reported in Holczer *et al.* (2016).

Common name	Name		Variation	
	KOI	KIC	$P$ (d)	$A$ (m)
Kepler-39 b	423.01	9478990	1393(81)	1.9(3)
Kepler-52 d	775.03	11754553	1493(300)	9(4)
Kepler-89 c	94.02	6462863	395(10)	10(2)
Kepler-110 b	124.01	11086270	767(23)	12(4)
Kepler-110 c	124.02	11086270	1245(13)	6(2)
Kepler-122 e	232.04	4833421	1135(59)	42(6)
Kepler-142 d	343.03	10982872	1400(5)	57(9)
Kepler-166 c	481.03	11192998	1419(81)	20(5)
Kepler-196 c	612.02	6587002	1431(197)	7(1)
Kepler-201 c	655.02	5966154	828(88)	11(4)
Kepler-222 d	723.02	10002866	770(23)	5(1)
Kepler-222 c	723.03	10002866	606(11)	3.2(5)
Kepler-227 c	752.02	10797460	1041(12)	14(8)
Kepler-230 c	759.02	11018648	776(60)	19(6)
Kepler-233 c	790.02	12470844	1057(127)	12(5)
Kepler-267 d	1078.03	10166274	818(24)	8(2)
Kepler-283 c	1298.02	10604335	1212(36)	68(11)
Kepler-299 e	1432.04	11014932	1427(102)	74(46)
Kepler-300 c	1435.01	11037335	1365(104)	58(10)
Kepler-310 c	1598.01	10004738	1004(10)	5(2)
Kepler-310 b	1598.03	10004738	1134(49)	15(3)
Kepler-358 c	2080.01	10864531	810(3)	19(6)
Kepler-362 c	2147.01	10404582	851(85)	14(6)
Kepler-364 c	2153.01	10253547	696(66)	23(4)
Kepler-509 b	276.01	11133306	1506(138)	4(1)
Kepler-549 c	427.03	10189546	978(43)	42(8)
Kepler-672 b	773.01	11507101	707(32)	14(3)
Kepler-795 b	1218.01	3442055	731(27)	10(4)
Kepler-797 b	1238.01	6383821	895(60)	37(11)
Kepler-807 b	1288.01	10790387	1327(97)	1.8(5)
Kepler-852 b	1444.01	11043167	1123(76)	15(3)
Kepler-966 b	1828.01	11875734	1162(120)	7(2)
Kepler-1036 b	1980.01	11769890	1382(84)	16(2)
Kepler-1097 b	2102.01	7008211	729(29)	9(1)
Kepler-1126 b	2162.01	9205938	1327(133)	23(6)
Kepler-1129 c	2167.03	6041734	1236(117)	19(4)
Kepler-1184 b	2309.01	10010440	1108(51)	24(5)
Kepler-1185 b	2311.03	4247991	820(89)	9(3)
Kepler-1388 b	2926.01	10122538	370(19)	18(7)
Kepler-1389 b	2931.01	8611257	1312(101)	43(8)
Kepler-1453 b	3280.01	10653179	1078(2)	22(10)
Kepler-1524 b	3878.01	4472818	974(77)	4(1)
Kepler-1527 b	3901.01	9480535	1024(25)	44(5)
Kepler-1530 c	3925.03	10788461	86.4(6)	13(3)
Kepler-1552 b	4103.01	3747817	998(125)	28(8)
Kepler-1593 b	4356.01	8459663	1465(134)	28(9)
Kepler-1638 b	5856.01	11037818	840(51)	197(32)

Archive is 8.041 d, but the reference (Xie 2014) for it is quite old and only used data up to quarter Q16. We also employed Q17 data in this paper. In many other cases, the ephemeris given by the archive is not the latest one. An incorrect value for the period could mean that the transit will really be observed a few hours earlier or later than it would

be calculated, after a few years. An observer with an outdated ephemeris will not see any transit at all. After removing the linear trend determined by the new ephemeris, we can obtain residual TTV with no other significant changes (right) (see note 1 in Table 1).



**Fig. 3** Examples of exoplanets with chaotic (abnormal) TTVs (see note 3 in Table 1).

Residual TTVs of 64 planets show periodic or quasi-periodic variations (see note 2 in Table 1). The examples of such systems with more or less significant changes are depicted in Figure 2. TTVs of 17 planets from this group have already been analysed by Holczer et al. (2016). We compared our results with theirs in Table 2. Periodic TTV signals of six planets (Kepler-52 d, Kepler-89 c, Kepler-122 e, Kepler-166 c, Kepler-283 c and Kepler-549 c) were already reported by Thompson et al. (2018) but they did not determine any parameters associated with these changes. Forty-three of these planets with periodic TTVs have not been reported in any other paper. Discovering these new TTV systems was a result of using our method of LC detrending and time of transit measurement. All the planets with unreported periodic TTVs and six planets reported (but not analysed) by Thompson et al. (2018) are listed in Table 3 with the periods and amplitudes of TTV changes. We used a sinusoidal model of these variations to determine their periods and amplitudes. For finding correct values of sinusoidal model parameters, we ran a simple Levenberg-Marquardt algorithm (Marquardt 1963). Amplitudes of the variations found vary between approximately 2 and 70 min and periods vary from just 80 to more than 1500 d. These changes could be caused by interaction

with another body(ies) (e.g. Agol et al. (2005)), stellar activity (e.g. spots) or other effects in the studied systems.

Ninety-five exoplanets show chaotic or abnormal TTVs (see note 3 in Table 1). This type of variation is most probably caused by stellar activity (e.g. Oshagh et al. (2013)) and/or gravitational interaction with other bodies in the systems. Examples of these systems are shown in Figure 3.

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## References

- Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, *MNRAS*, 359, 567
- Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, *PASP*, 125, 989
- Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Science*, 327, 977
- Fabrycky, D. C., Ford, E. B., Steffen, J. H., et al. 2012, *ApJ*, 750, 114
- Gajdoš, P., Parimucha, Š., Hambálek, Ľ., & Vaňko, M. 2017, *MNRAS*, 469, 2907

- Holczer, T., Mazeh, T., Nachmani, G., et al. 2016, *ApJS*, 225, 9
- Howell, S. B., Sobeck, C., Haas, M., et al. 2014, *PASP*, 126, 398
- Mandel, K., & Agol, E. 2002, *ApJ*, 580, L171
- Marquardt, D. W. 1963, *Journal of the Society for Industrial and Applied Mathematics*, 11, 431
- Oshagh, M., Santos, N. C., Boisse, I., et al. 2013, *A&A*, 556, A19
- Sing, D. K. 2010, *A&A*, 510, A21
- Steffen, J. H., Fabrycky, D. C., Ford, E. B., et al. 2012, *MNRAS*, 421, 2342
- Thompson, S. E., Coughlin, J. L., Hoffman, K., et al. 2018, *ApJS*, 235, 38
- Wang, S., & Ji, J. 2014, *ApJ*, 795, 85
- Wang, S., & Ji, J. 2017, *AJ*, 154, 236
- Xie, J.-W. 2014, *ApJS*, 210, 25