Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S1743921318002818

Kepler-410Ab and Transit Timing Variations

P. Gajdoš, Š. Parimucha and M. Fedurco

Institute of Physics, Faculty of Natural Sciences, Šafárik University, Košice, Slovakia
email: pavol.gajdos@student.upjs.sk

Abstract. Our poster presented a new analysis of the transit-time variations displayed by the extrasolar planet Kepler-410Ab. We assumed that the observed changes in the transit times are caused by the gravitational influence of another body in the system. To determine the mass of that perturbing body, we considered the light-time effect and an analytical approximation of the perturbation model. The solutions resulting from both methods gave comparable results, with an orbital period of 970 days and a slightly eccentric orbit for the third body. We proposed two possible models of a perturbing body orbiting a common barycentre with Kepler-410A: a single star with mass of at least 0.906 $M_\odot$, or a binary star with a total component mass of at least 2.15 $M_\odot$.

Keywords. Eclipses; planets and satellites: individual (Kepler-410Ab); techniques: photometric; stars: binaries: general

---

1. Introduction

Kepler 410 is a binary star system whose smaller member, Kepler 410B, was discovered by Adams *et al.* (2012) using adaptive optics; it is separated from the brighter member by an angular distance of $1''.63$. An exoplanet (Kepler-410Ab), transiting Kepler-410A, was then discovered by the *Kepler* satellite in 2013 and confirmed by Van Eylen *et al.* (2014), who showed that it is a Neptune-sized planet in a 17.8336-day orbit. Transit-time variations (TTVs) of Kepler-410Ab were reported for the first time by Mazeh *et al.* (2013) and partially analysed by Van Eylen *et al.* (2014). An analysis of TTVs detected in the system has also been presented by Gajdoš *et al.* (2017).

2. Determination of Transit Times

To determine the individual times of transit we used short-cadence de-trended data (PDCSAP_FLUX) provided by the NASA Exoplanet Archive. Our procedure was as follows:

- We extracted parts of the light-curve around detected transits, where we took an interval ± 0.2 days around the computed transit time and removed additional residual trends (caused by pulsations of the host star) by fitting the out-of-transit parts of light-curve with a second-order polynomial function. We also subtracted an 8% flux contamination issuing from the wide companion, Kepler-410B.
- We determined transit parameters (see Table 1) from stacked transit light-curves by our software implementation of a Mandel & Agol (2002) model using Monte-Carlo MCMC simulation. From those parameters we created a template of the transit (Fig. 1).
- For each of 70 individual transits the time of transit, T_T, was then determined using the template.

Table 1. Transit parameters of exoplanet Kepler-410Ab.

Parameter	Value
semi-major axis, a [au]	0.1226 (47)[a]
planet radius, r_{p} [$R_{\oplus}$]	2.647 (20)
orbital inclination, i [deg]	87.744 (3)
sum of squares, χ^2	33181.59

[a] adopted from Van Eylen *et al.* (2014)

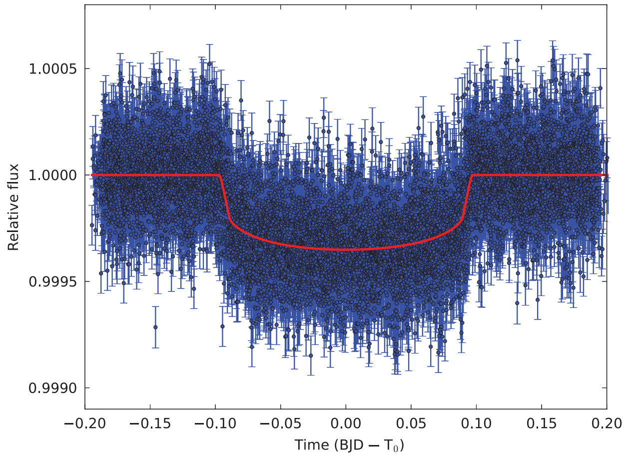

Figure 1. Stacked transits of Kepler-410Ab and the best-fitting template. Reproduced from Gajdoš *et al.* (2017).

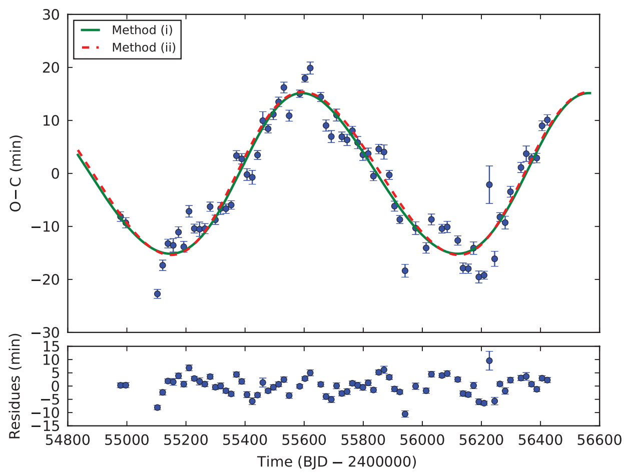

Figure 2. The (O–C) diagram of Kepler-410Ab, constructed according to the improved linear ephemeris. Reproduced from Gajdoš *et al.* (2017). A description of the methods used is given in Sect. 3.

A new, improved linear ephemeris was determined using the values of T_T which were calculated from

$$T_{\mathrm{T}} = 2455014.23765(22) + 17.8336313(43) \times E,$$

where E is the epoch of observation. Using that improved ephemeris, we constructed a corrected (O–C) diagram (Fig. 2).

Table 2. Parameters of the third body obtained from two methods described in Sect. 3.

Parameter	LiTE solution	Agol method
P_3 [days]	971.1 (3.7)	973.6 (3.6)
e_3	0.15 (2)	0.09 (1)
t_{03} [BJD2450000]	5440 (15)	5372 (2)
$a_{12} \sin i_3$ [au]	1.839 (20)	–
ω_3 [deg]	25.8 (5.8)	–
μ_3	–	0.428 (41)
$f(M_3)$ [$M_\odot$]	0.879 (30)	–
M_3 [$M_\odot$]	2.151 (78)	0.906 (155)
χ^2	804.9	831.5

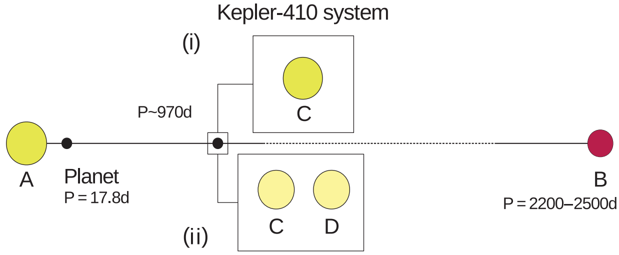

Figure 3. Schematic view of the Kepler-410 system (not to scale). Reproduced from Gajdoš *et al.* (2017).

3. Analysis of (O–C) Diagram

The transit times, T_T, which we determined show a periodic variation with an amplitude of approximately 30 minutes and a period between 950 and 1000 days, in agreement with previous analyses by Mazeh *et al.* (2013) and Van Eylen *et al.* (2014).

By assuming that the observed TTVs are due to the gravitational influence of another body (planet or star) in the system, we could calculate δT to find the physical parameters of the perturbing body. We used two different approaches:

• Method (i): LiTE (light-time effect) solution (Irwin 1952), a method often used to detect an unseen companion in a binary star;

• Method (ii): an analytical approximation to the perturbation model given in Agol *et al.* (2005).

To obtain the optimal parameters with statistically significant precision in both approaches, we used our own code based on genetic algorithms and MCMC simulation. A full description of our code is being published in Gajdoš & Parimucha (2018). The results from both methods are listed in Table 2 and illustrated in Fig. 2.

4. Discussion and Conclusion

Our interpretation is based on a natural assumption that TTVs are caused by the gravitational influence of another body in the system. Both methods that we applied give similar results: an orbital period $P_3 \sim 970$ days, and a slightly eccentric orbit for the third body. By adopting the LiTE solution, we determined a mass function of $f(M_3) = 0.879(30)$ $M_\odot$. For a coplanar orbit we derived a minimal mass for the body of $M_3 = 2.151(78)$ $M_\odot$. Somewhat similarly, by using the analytical approximation given by Agol *et al.* (2005) we obtained a minimum mass for the perturbing body of $M_3 = 0.906(155)$ $M_\odot$. These values can be considered as limiting masses for the third body.

We propose the following models to explain the observed TTVs in the transits of Kepler-410A (Fig. 3). The perturbing body is either

https://doi.org/10.1017/S1743921318002818 Published online by Cambridge University Press

(i) a star with a minimum mass of 0.91 $M_{\odot}$, in orbit around the common barycentre with Kepler-410A with a period of ∼970 days, or

(ii) a non-eclipsing binary star with a minimum total mass of 2.15 M⊙, that forms an hierarchical system with Kepler-410 We note that the component Kepler-410B is a cool red dwarf in a distant orbit with a period of over 2200 years, so it cannot be the originator of the observed TTVs.

Acknowledgements

This research has been supported by grant no. APVV-15-0458 from the Slovak Research and Development Agency, and through project ITMS no. 26220120029 in a supporting operational research and development programme financed by the European Regional Development Fund.

References

Adams, E. R., *et al.* 2012, *AJ*, 144, 42
Agol, E. *et al.* 2005, *MNRAS*, 359, 567
Gajdoš, P., *et al.* 2017, *MNRAS*, 469, 2907
Gajdoš, P., Parimucha, Š. 2018, *Astron. Comput.*, *2019ascl.soft01002G*
Irwin, J. B. 1952, *ApJ*, 116, 211
Mandel, K., & Agol, E. 2002, *ApJ*, 580, L171
Mazeh, T., *et al.* 2013, *ApJS*, 208, 16
Van Eylen, V., *et al.* 2014, *ApJ*, 782, 14

https://doi.org/10.1017/S1743921318002818 Published online by Cambridge University Press