Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 179-181

Search for exomoons in the exomoon corridor using Kepler data

J. Aires[1] & L. A. Almeida[2]

[1] Departamento de Física, Universidade Federal do Rio Grande do Norte, 59072-970 Natal-RN, Brazil e-mail: `joao.aires.706@ufrn.edu.br`
[2] Escola de Ciências e Tecnologia, Universidade Federal do Rio Grande do Norte, Campus Universitário, Natal-RN 59072-970, Brazil e-mail: `leonardo.almeida@ufrn.br`

Abstract. As we reached the milestone of 6000 detected exoplanets, we still have not undoubtedly detected any exomoon. To select the best targets for further exomoon searching campaigns, this initial work rederived the Transit Timing Variations (TTVs) and Transit Duration Variations (TDVs) for 4 Kepler Objects of Interest (KOIs). Each KOI has only one confirmed exoplanet with a TTV period between 2 and 4 times the transiting exoplanet's period — a range known as the "exomoon corridor". We found that only one target (KOI-2469b) did not show statistically significant TTV and TDV signals. We are currently conducting further analysis on all other targets to fully characterize the perturbing body.

Resumo. Embora a marca de 6000 exoplanetas detectados ser atingida, ainda não detectamos, de maneira inequívoca, qualquer exolua. Para selecionar os melhores alvos para futuras campanhas de busca por exoluas, este trabalho inicial redeterminou as variações nos instantes de trânsito (do inglês, TTVs) e as variações na duração do trânsito (do inglês, TDVs) para 4 objetos de interesse do Kepler (do inglês, KOIs). Cada KOI possui apenas um exoplaneta confirmado e períodos de TTV entre 2 e 4 vezes o período do exoplaneta transitante - intervalo de períodos conhecido como "corredor das exoluas". Nós encontramos que apenas um alvo (KOI-2469 b) não apresentou variações estatisticamente significativas em ambos TTV e TDV. Análises adicionais estão sendo feitas em todos os outros alvos, afim de caracterizar completamente o corpo perturbador.

Keywords. Planets and satellites: general – Planets and satellites: detection – Planets and satellites: fundamental parameters

1. Introduction

Moons are common in the Solar System. In fact, we know of more than 200 moons in our own planetary system, the majority of them in multi-moon systems. This scenario suggests that not only are moons likely ubiquitous in the Universe, but also that multi-moon systems might be the rule in planetary systems outside our own. In September 2025, the community reached the remarkable milestone of 6000 detected extrasolar planets (hereafter exoplanets), most of which were discovered through transit, radial velocity, and microlensing events, as reported by the NASA Exoplanet Archive[1].

Many exoplanets have emerged as candidate hosts for extrasolar moons (hereafter exomoons), e.g., Kepler-1625 b (Teachey & Kipping 2018; Rodenbeck et al. 2018; Heller & Hippke 2024) and Kepler-1708,b (Kipping et al. 2022; Heller & Hippke 2024). However, we have not unambiguously detected any extrasolar moon to date. Among all methods proposed to search for exomoons, the analysis of the stellar photometry of transiting exoplanets is, by far, the most applied in the literature (Brown et al. 2001; Kipping et al. 2012). Researchers apply this method either by searching for direct evidence, such as exomoon transits, or through indirect evidence, such as the presence of Transit Timing Variations (hereafter TTVs) and Transit Duration Variations (hereafter TDVs) in the transiting exoplanetary companion.

The analysis of Transit Timing Variations (TTVs) and Transit Duration Variations (TDVs) in the photometry of a transiting exoplanet is a valuable method for characterizing the mass and orbit of potential exomoons. Kipping (2009) demonstrated that the amplitude of the TTV signal generated by a satellite scales as $\propto M_S a_S$, where M_S and a_S are the mass and semi-major axis of the satellite, respectively. Conversely, the TDV signal amplitude scales as $\propto M_S a_S^{-1/2}$. Consequently, the ratio of these amplitudes allows for the independent determination of the satellite's mass and semi-major axis.

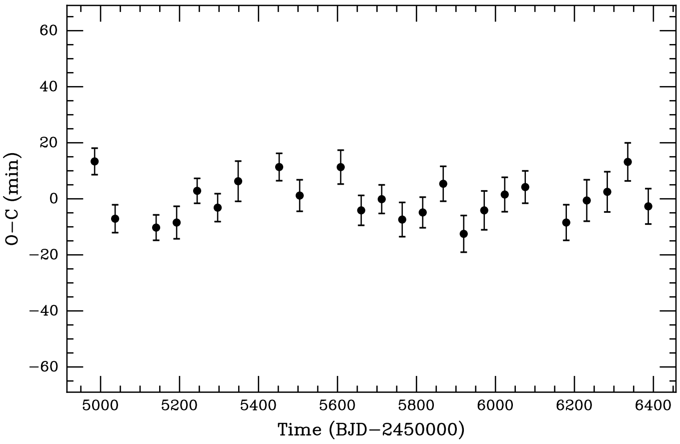
Recently, Kipping (2021) proposed that approximately half of exomoons are expected to induce TTVs with periods between 2 and 4 times the orbital period of their host planet, a frequency range where planet-planet induced TTVs are unlikely to manifest. This specific range, known as the "exomoon corridor", represents a simple yet powerful tool for identifying systems where TTV signals are more likely caused by an exomoon, enabling the prioritization of these targets.

In this work, we derive TTV and TDV series using a statistically robust pipeline for four single-planet systems observed by Kepler that exhibit TTV signals within the exomoon corridor. In Sec. 2, we describe the sample selection criteria. Sec. 3 details the transit analysis and the derivation of the TTV and TDV measurements. Finally, Sec. 4 presents our initial results, followed by our conclusions in Sec. 5.

2. Sample selection

To construct our sample of Kepler targets with significant TTVs, we used the comprehensive collection of 2599 Kepler Objects of Interest (hereafter, KOIs) that show TTV signals, as compiled by Holczer et al. (2016). Although the full catalog includes multi-planet systems, our goal was to isolate signals not attributable to known companions. Therefore, we cross-matched the KOIs with the NASA Exoplanet Archive using the Python package `astroquery` (Ginsburg et al. 2019) and selected only those systems with a single confirmed exoplanet (flag `sy_pnum = 1`). In addition, we required targets to have at least three observed transits in the Kepler data and TTV modulation periods ranging between 2 and 4 times the orbital period of the transiting exoplanet. This specific window corresponds to a regime where planet-

[1] `https://exoplanetarchive.ipac.caltech.edu`



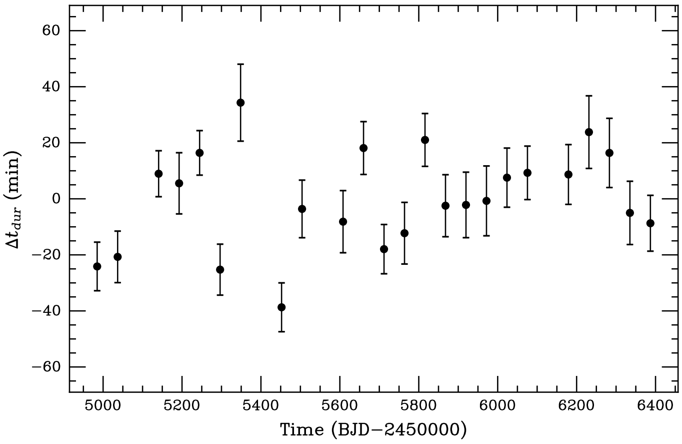


Figure 1. *Left panel*: $O - C$ diagram obtained from the transits of KOI-1355 b. *Right panel*: corresponding TDV diagram for the same target.

planet interactions rarely induce TTV signals, but is expected to contain the signatures of approximately 50% of exomoons (Kipping 2021).

The selection procedure yielded ten KOIs. However, following a visual inspection of their Kepler light curves retrieved from the Exo.MAST portal[2], we refined the final sample to four KOIs that exhibited clearly discernible transit signals. These targets are: KOI-1355,b, KOI-1429,b, KOI-2469,b, and KOI-3762,b.

3. Data analysis

To obtain the variations in the mid-transit times (t_{mid}) and in the planetary transit durations (t_{dur}), we first performed a transit-by-transit fit for all KOIs in our sample. We modeled the transit signal in the light curve using the `batman` package (Kreidberg 2015) together with the Markov Chain Monte Carlo (MCMC) method, implemented through the `emcee` package (Foreman-Mackey et al. 2013). We set the t_{mid} for each epoch, the planet-to-star radius ratio $R_p/R_\star$, the semi-major axis in units of the stellar radius $a_p/R_\star$, and the orbital inclination angle i as free parameters.

We derived t_{dur} by interpolating the best-fit model onto a grid of 10 000 points, defining the $t_{\text{dur}} = t_{\text{exit}} - t_{\text{entry}}$, the interval between the points where the flux departs from and returns to the out-of-transit level. Assuming the transit profile is symmetric about t_{mid}, we can write:

$$t_{\text{mid}} = \frac{t_{\text{entry}} + t_{\text{exit}}}{2} \tag{1}$$

where t_{entry} and t_{exit} denote the ingress and egress times of the transit, respectively. Through error propagation, the uncertainty is given by:

$$\sigma_{t_{\text{dur}}} = 2\,\sigma_{t_{\text{mid}}} \tag{2}$$

where $\sigma_{t_{\text{dur}}}$ and $\sigma_{t_{\text{mid}}}$ are the uncertainties t_{dur} and t_{mid}, respectively. All other parameters, treated as fixed, were retrived from the Exo.MAST portal. For all KOIs, we adopted a quadratic limb-darkening law, deriving the coefficients u_1 and u_2 by interpolating the tables from Claret & Bloemen (2011). For the MCMC analysis, we employed uniform priors and utilized 52 walkers running for 10,000 steps, discarding the initial 5000 iterations as a burn-in.

[2] https://exo.mast.stsci.edu

The next step was to obtain the mid-transit time observed minus calculated diagram (hereafter, $O-C$) for all KOIs. To achieve this, we fitted a linear ephemeris to the t_{mid} series of each target, similarly to what we described in the previous paragraph. The resulting diagrams show the delays and advances in transit timing. We expect any significant gravitational interaction between the transiting exoplanet and an external body to appear in this diagram. The left panel in Figure 1 displays a representative $O-C$ diagram for one of the KOIs in our sample. Correspondingly, the right panel illustrates the variation in t_{dur} for the same target, where mean duration was subtracted to recenter the diagram around zero.

4. Results

Upon applying the methodology outlined in Sec. 3 to our sample, we observed that only KOI-2469 b exhibits no significant TDV, although a marginal TTV signal is discernible in the $O-C$ diagram. Figure 2 shows both the $O - C$ (left panel) and TDV (right panel) diagrams for this target. We interpret these results as indicating the absence of an exomoons sufficiently massive to induce statistically significant gravitational perturbations on the transiting planet. In contrast, the remaining KOIs in our sample warrant a more detailed analysis to accurately constrain the parameters of the potential perturbers. Specifically, we know that the TDV signals induced by exomoons must have the same period but a $\pi/2$ phase shift (Kipping 2009) relative to the TTV signal. Furthermore, the TTV signal itself is expected to be undersampled due to the sampling rate relative to the satellite's orbital period (Kipping 2021).

5. Conclusions

In this work, we present initial results from our search for exomoon-induced TTV and TDV signals in the Kepler data of four KOIs. Our analysis indicates that KOI-2469 b is the only target that does not exhibit a significant TDV signal. We interpret this as possible absence of exomoons sufficiently massive to induce statistically detectable perturbations on the planet's transit duration. For the remaining KOIs, we are conducting a more detailed analysis of both TTV and TDV series to constrain the source of these perturbations and to definitively confirm or reject the exomoon nature.

Acknowledgements. All authors would like to thank the organizers of the XLVIII RASAB for the event. J. Aires would like to thank the Coordination for the

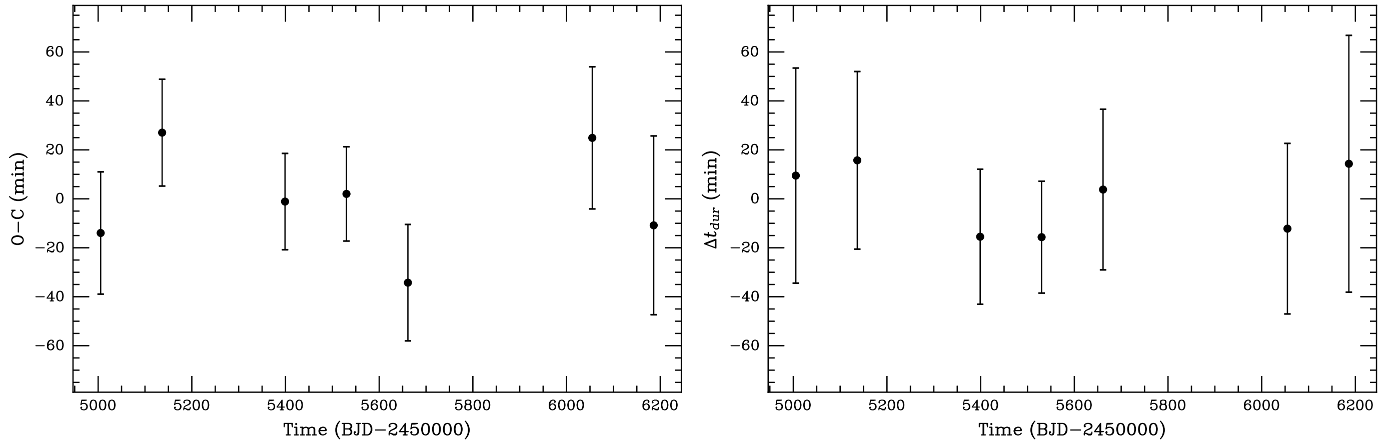


Figure 2. *Left panel*: $O - C$ diagram obtained from the transits of KOI-2469 b. *Right panel*: corresponding TDV diagram for the same target.

Improvement of Higher Education Personnel (CAPES) for financial support and Universidade Federal do Rio Grande do Norte (UFRN) through the physics graduate program PPGF/UFRN. This work was also supported by CNPq/Brazil (grant number 302414/2022-3).

References

Brown T. M., Charbonneau D., Gilliland R. L., Noyes R. W., Burrows A., 2001, ApJ, 552, 699.
Claret A., Bloemen S., 2011, A&A, 529, A75.
Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, PASP, 125, 306.
Ginsburg A. et al., 2019, AJ, 157, 98.
Heller R., Hippke M., 2024, NatAs, 8, 193.
Hippke M., 2015, ApJ, 806, 51.
Holczer T., Mazeh T., Nachmani G., Jontof-Hutter D., Ford E. B., Fabrycky D., Ragozzine D., Kane M., Steffen J. h, 2016, ApJS, 225, 9.
Kipping D. M., 2009, MNRAS, 392, 181. doi:10.1111/j.1365-2966.2008.13999.x
Kipping D. M., Bakos G. Á., Buchhave L., Nesvorný D., Schmitt A., 2012, ApJ, 750, 115.
Kipping D., 2021, MNRAS, 500, 1851.
Kipping, D., Bryson, S., Burke, C. et al. Nat Astron 6, 367–380 (2022).
Kreidberg L., 2015, PASP, 127, 1161.
Rodenbeck K., Heller R., Hippke M., Gizon L., 2018, A&A, 617, A49.
Teachey A., Kipping D. M., 2018, SciA, 4, eaav1784.