

CHARACTERIZING EXOPLANET TRANSITS AND STELLAR ACTIVITY IN KEPLER LIGHTCURVES WITH SCALABLE GAUSSIAN PROCESSES. V. Foing¹ (vickyfoing@gmail.com) and A. M. Heras² and B. Foing², ¹University of Amsterdam, ²European Space Agency (ESTEC).

Introduction: In the past decade, Gaussian Processes (GPs) have become popular models for modelling both instrumental and astrophysical noise in lightcurves to improve the characterization of exoplanet transits. In this work, we apply scalable GP models using the software *celerite* to characterize exoplanet transits and stellar activity in Kepler lightcurves [1]. Our aim is to build GP models which can retrieve accurate transit and rotation parameters, with a focus on the radius of the planet and the rotation period of the star. Furthermore, we investigate the extent to which joint modelling improves overall characterization.

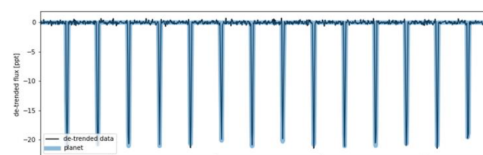


Figure 1a: Exoplanet transits.



Figure 1b: Stellar activity (rotation).

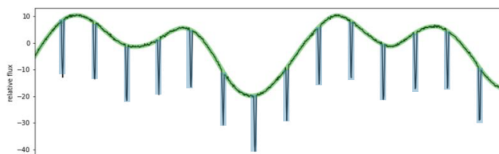


Figure 1c: Joint modelling of both signals.

Methodology: We develop a pipeline which automates multiple stages of data analysis. First, the pipeline *preprocesses the lightcurves*, which involves selecting PDCSAP instrumental correction [2]. Second, the pipeline makes *initial estimates* of the parameters using traditional Physics techniques. We use the Transit Least Squares algorithm by [3] to detect the transits and estimate the planet radius, transit period, and the first transit time, and the Lomb-Scargle Periodogram by [4] to estimate the stellar rotation period. Third, the pipeline *builds the GP model* using the exoplanet toolkit so that the mean function captures the transit signals and the kernel function captures the noise and stellar activity [4][5]. We use *starry*'s limb-darkened lightcurve to model the transit signals, *celerite*'s stochastically-driven damped harmonic oscillator (SHO) kernel to model

background noise, and *celerite*'s quasi-periodic Rotation kernel to model rotational modulation [1][6]. The GP model is trained on the lightcurve data, providing a posterior distribution over the parameters. Fourth, the pipeline performs *MCMC sampling* using PyMC3's No U-Turn (NUTS) sampler to approximate the posterior distributions of the parameters [7].

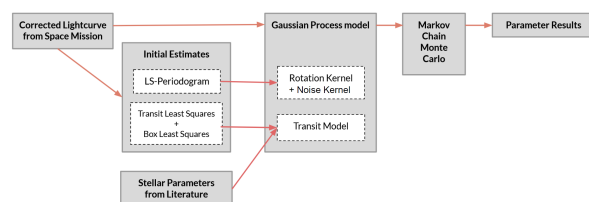


Figure 2: The pipeline automates multiple stages of data analysis: instrumental correction, initial parameter estimates, GP modelling, and MCMC sampling.

Experiments: To assess the benefits of jointly modelling the rotational modulation and the transits, we compare the performances of three GP models: ExoGP (only transit), RotGP (only rotation), and the joint ExoRotGP (rotation and transit). ExoGP consists of a noise kernel and a transit mean model, RotGP consists of rotation kernel and zero mean function, and ExoRotGP consists of noise and rotation kernel and a transit mean model. The models are applied to 9 Kepler lightcurves with confirmed planets and stellar rotation periods and the parameter estimates obtained are compared to those from refereed publications.

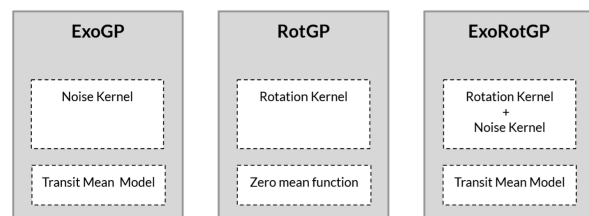


Figure 3: Model architectures: ExoGP (only transit), RotGP (only rotation), ExoRotGP (rotation and transit)

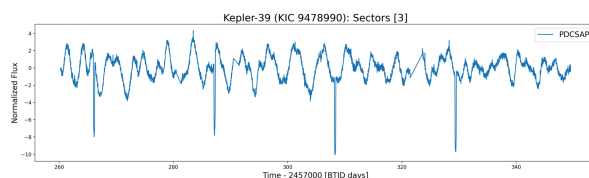


Figure 4: Kepler data has a cadence of 30 minutes and Quarters (Qtr) ranging from 30 to 90 days.

Results: For all 9 Kepler targets, the joint ExoRotGP model obtains stellar rotation periods within one day of the reference rotation periods, which range from 4.5 days to 27.5 days.

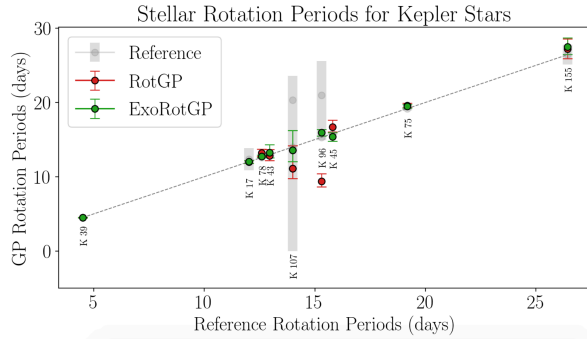


Figure 5: Rotation periods obtained by RotGP (red) and ExoRotGP (green) plotted with reference rotation periods (grey). ExoRotGP performs better than RotGP for Kepler-107, Kepler-96, and Kepler-45.

Star	Qtr	ExoRotGP P _{rot} (days)	Reference P _{rot} (days)
Kepler-107	2	13.6 ^(-1.5,+2.6)	<20.3 ^{+3.3}
Kepler-155	5	27.5 ^(-1.0,+1.2)	26.43 ^{±1.32}
Kepler-17	1	12 ^(-0.2,+0.1)	12.01 ^{±0.16}
Kepler-39	3	4.5 ^{±0.1}	4.5 ^{±0.07}
Kepler-43	1	13.3 ^(-0.7,+1.0)	12.95 ^{±0.25}
Kepler-45	1	15.4 ^(-0.6,+0.5)	15.8 ^{±0.2}
Kepler-78	1	12.7 ^{±0.2}	12.588 ^{±0.03}
Kepler-75	1	19.5 ^{±0.2}	19.18 ^{±0.25}
Kepler-96	2	15.9 ^{±0.4}	15.3

For all 9 Kepler targets, the joint ExoRotGP model obtains planet radii within one standard deviation of the reference radii, which range from super Earths to Jupiters. Furthermore, we observe that the accuracy of the radii improves when integrating over the exposure time (a feature of the starry software). This reaffirms the claim by [8] that long cadence photometry can lead to morphological distortions in the transit shape that need to be corrected with numerical integration techniques.

Planet	Qtr	ExoRotGP Radius (R _{Jup})	Reference Radius (R _{Jup})
Kepler-107 e	2	0.2709 ^{±0.01}	0.259 ^{±0.003}
Kepler-155 b	5	0.1571 ^{±0.01}	0.154 ^(-0.024,+0.025)
Kepler-17 b	1	1.3761 ^{±0.04}	1.33 ^{±0.04}
Kepler-39 b	3	1.1853 ^(-0.09,+0.08)	1.24 ^(-0.1,+0.09)
Kepler-43 b	1	1.169 ^{±0.05}	1.16 ^(-0.03,+0.04)
Kepler-45 b	1	0.9878 ^{±0.14}	0.96 ^{±0.11}
Kepler-78 b	1	0.1091 ^{±0.01}	0.1 ^{±0.01}
Kepler-75 b	1	1.0508 ^(-0.06,+0.05)	1.05 ^{±0.03}
Kepler-96 b	2	0.2284 ^{±0.02}	0.238 ^{±0.02}

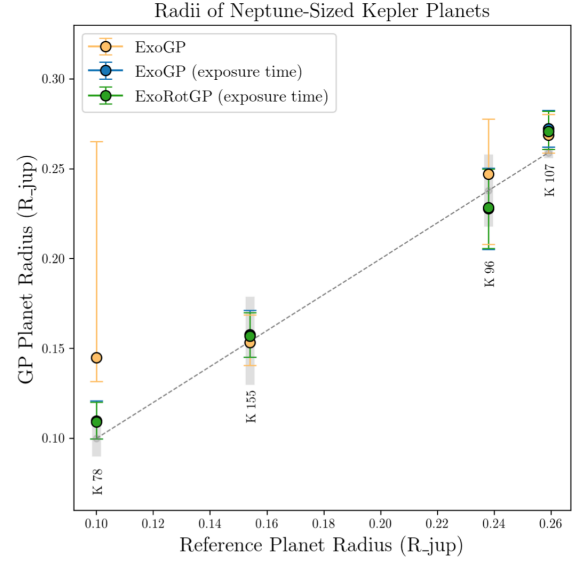


Figure 6: Planet radii obtained by ExoGP (blue) and ExoRotGP (green) plotted with reference radii (grey). ExoRotGP performs marginally better than ExoGP.

Discussion: Our results demonstrate that the joint ExoRotGP model recovers accurate transit and rotation parameters from the Kepler data. We further highlight the importance of exposure time integration techniques in the recovery of accurate planet parameters from long cadence data. When comparing the joint ExoRotGP model with the ExoGP model without a Rotation kernel, we discover that joint modelling only marginally improves the planet radii estimates. This suggests that celerite's noise kernel can be effective for removing stellar activity. Our results further indicate that the joint ExoRotGP model could be a promising tool for the characterization of small exoplanets, with sizes between Neptune and Earth. Our method provides a solid basis for a future application and extension of the model to these objects.

Acknowledgments: This research has made use of reference values from the NASA Exoplanet Archive and tutorials by the developers of the exoplanet toolkit [4].

References:

- [1] Foreman-Mackey D. et al. (2017) *AJ*, 154, 220.
- [2] Lightcurve Collaboration. (2018) *ASCL*, 1812.013.
- [3] Hippke, M. and Heller, R. (2019) *A&A* 623, A39.
- [4] Foreman-Mackey et al. (2020). DOI 10.5281/zenodo.1998447. [5] Astropy Collaboration. (2018) *AJ*, 156, 123. [6] Luger R. et al. (2019) *AJ*, 157, 64. [7] Salvatier, J. et al. (2016) *PeerJ Computer Science*, 2, e55. [8] Kipping D. M. (2010) *MNRAS*, 408, 1758-1769.