A Likelihood Search for Exomoons

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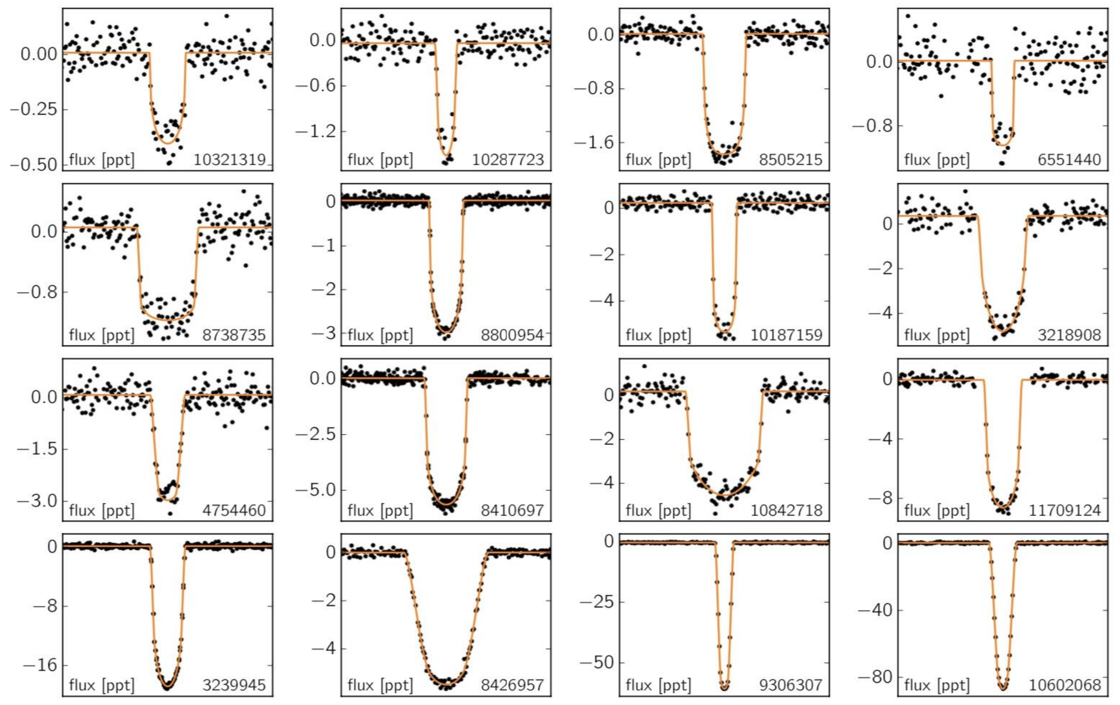
INTRODUCTION

- As of today, the community has found thousands of exoplanets, but zero exomoons; and yet moons are common in the Solar System.
- We believe the best exoplanet candidates to host exomoons are Jupiter-like with long periods, because they will have large Hill spheres.
- Within the largest possible Hill spheres of sixteen planets' light curves, we calculate a surrogate for the likelihood for an exomoon in each location along the light curve by means of a cross-correlation function.
- This technique for exomoon discovery is simple and fast; it is appropriate for ESA Plato. We demonstrate the method on very long-period planets found in the NASA Kepler data.

OBJECTIVES

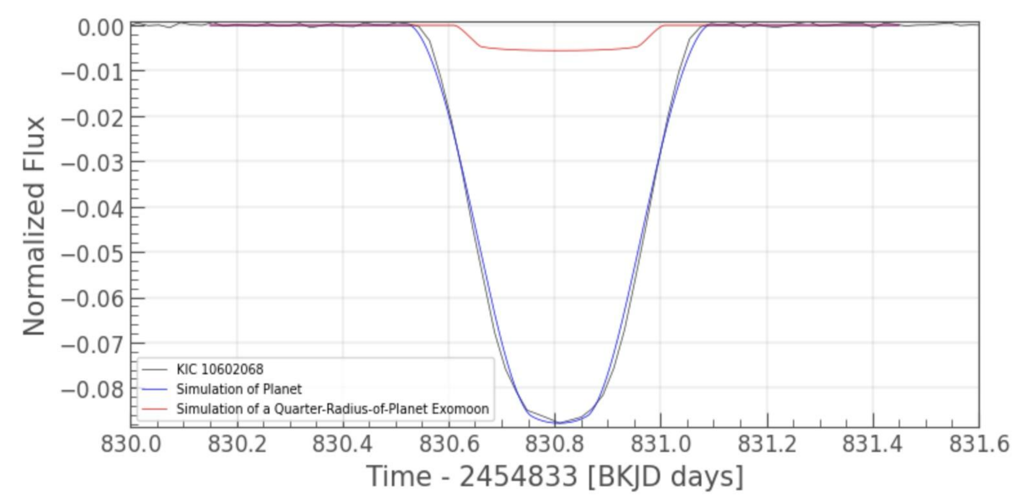
- From the sixteen planets below, we are creating a cross-correlation function in order to help us identify possible exomoons.
- For an exomoon, we expect to see positive spikes in correlation in a similar shape to that of the planet transit's correlation spike but scaled down in size.
- If there is a positive spike, we ensure that it is not a false positive by matching transit duration and transit dip, as we expect the exomoon's to be similar to the planet's.
- We plan to validate these spikes by means of injection testing.



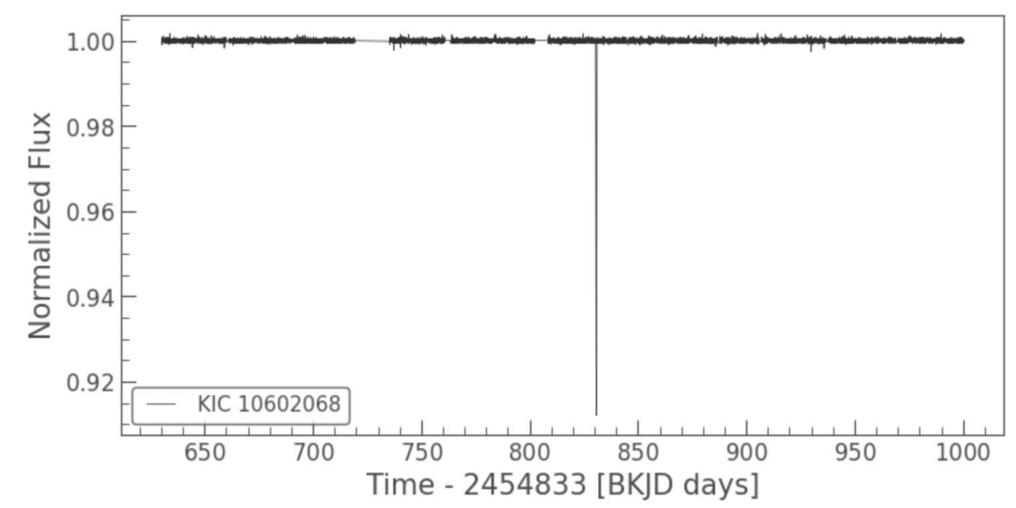
16 Large Radius, Long Period Jupiter Analogs Ideal for Exomoon Searches
(Foreman-Mackey, Morton, Hogg, et al.)

METHOD

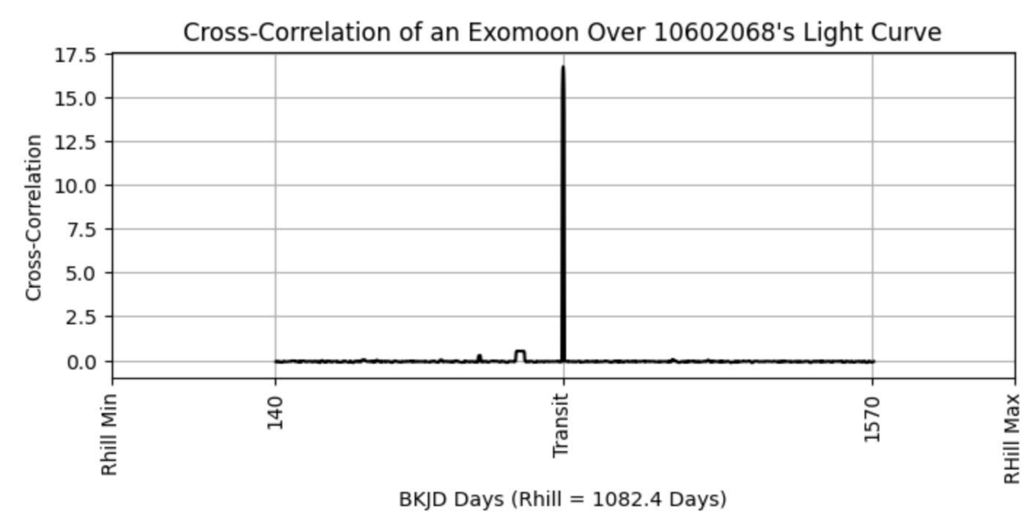
- For each single-transit-target we have a model for the exoplanet transit made with BATMAN (Kreidberg, 2015).
- For each target, we modify the exoplanet transit model to have 1/4 the radius but keep all other parameters (period, impact parameter, etc.) fixed.
- From Foreman-Mackey, Morton, Hogg et al. we used the largest possible radius and longest possible period in order to obtain the largest possible Hill radius for each planet. This ensures that we are validating or invalidating any result that could possibly be classifies as an exomoon around this planet.
- This model can be seen below in a single planet example. 10602068 is the only star's data plotted below, but we have done this for two other stars with their corresponding planet and follow the same method.
- This smaller-exoplanet model is a surrogate exomoon model. We permit the transit time for this second model t_0 to vary, and compute the cross-correlation with the Kepler data.



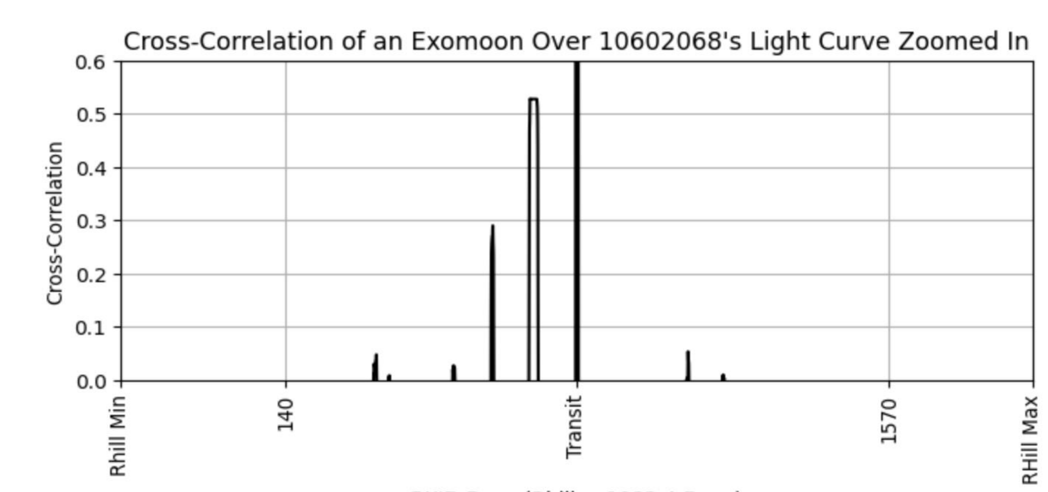
Transit Model (Blue) and Exomoon Transit Model (Red) Over the Transit Data (Black)



Entire Light Curve for 10602068, Including its Apparent Transit



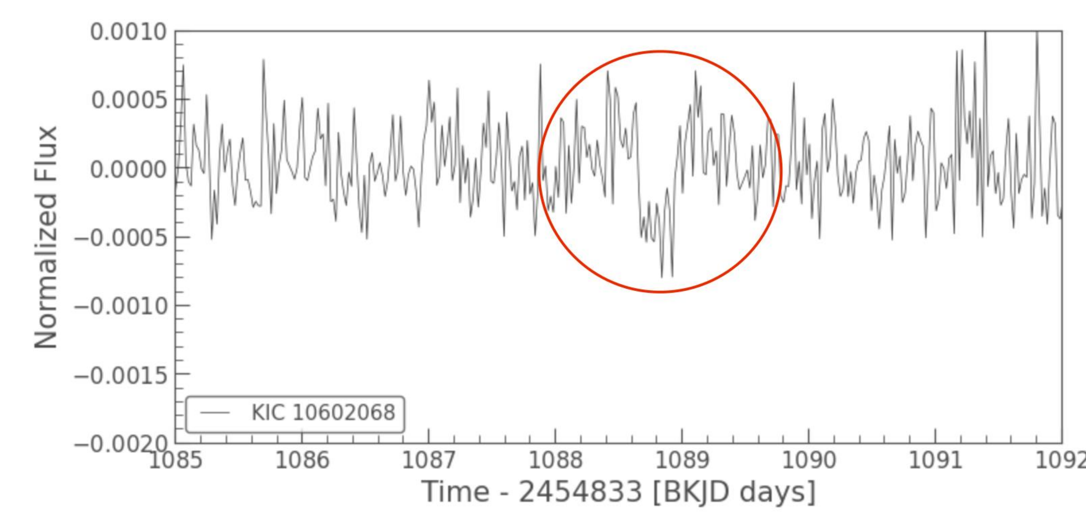
Top Left: Cross-Correlation of Exomoon Model Across Light Curve. Hill Radius = 1082.4



Bottom Left: Zoom in of Cross-Correlation of Exomoon Model Across Light Curve. Hill Radius = 1082.4

RESULTS

- Top Left: We ran the exomoon model across the light curve using a cross correlation function. The large spike is the planet's transit, which is a way to validate our filter is working. Other upward bumps are positive correlation, meaning there is something that is at least vaguely similar to an exomoon transit. This requires further examination in the following plots.
- Bottom Left: The same plot as in the Top Left, now zoomed in along the Y-axis. The positive spikes are a close up of the tiny bumps seen in the previous plot. The spikes may be an exomoon transit.
- Bottom Right: This is a very close look at the first spike to the right of the transit's spike from the Bottom Left. This has multiple data points that are below the mean, as well as the overall shape of a transit. This will require further tests in the future!



Bottom Right: Zoom in on Possible Exomoon Transit

CONCLUSIONS AND FUTURE RESEARCH

- Currently we have no clear exomoon detections around two of the planets we have examined (only one previously shown).
- The one possible exomoon shown is more difficult to validate as it has a very short transit duration as well as shallow depth.
- We plan to look closer at this result and similar results we have gotten from the other planets.
- The positive spikes you see are either from the transit, the shown data in question or transit-shaped errors in the light curve that we do not believe to be moons.
- The negative spikes indicate an inverse correlation. This indicates localized noise or spacecraft bias effects.
- With our exomoon candidates, we will use injection testing to validate or invalidate them.
- We are working towards completing our search and obtaining upper limits for the possible exomoons around these planets.

DATA

The 16 planets that we are searching were found by:

Foreman-Mackey, D., Morton, T. D., Hogg, D. W., Agol, E., & Schölkopf, B. (2016). The population of long-period transiting exoplanets. arXiv preprint arXiv:1607.08237v2. Retrieved from https://arxiv.org/abs/1607.08237v2

I am also using Kepler data:

Borucki, W. J., et al. (2010). Kepler Planet-Detection Mission: Introduction and First Results. Science, 327(5968), 977-980. DOI: 10.1126/science.1185402. Retrieved from https://doi.org/10.1126/science.1185402

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Kreidberg, L. (2015). *batman: BAsic Transit Model cAlculatioN in Python*. Publications of the Astronomical Society of the Pacific, 127, 1161. doi: 10.1086/683602

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