Searching for exomoons around the Kepler planetary candidates

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Introduction

Despite the efforts during the past 8 years that aimed on a discovery of an exomoon in the *Kepler* data (Deeg 2002, Szabó et al. 2006, Simon et al. 2007, 2009, 2010, 2012, Kipping 2009), there has no firm evidence for an exomoon found as of today (e.g. Szabó et al. 2013).
The apparent contradiction between the number of examined KOI systems by date and the lack of any firm detection is a significant observation urging for an explanation. Two obvious arguments can resolve this paradox:

- In fact quite few KOI planet candidates exhibit physical and photometrical parameters offering a STABLE AND DETECTABLE exomoon; or
- The size of exomoons cannot exceed significantly that of the moons in our Solar System, therefore they remain undetected.

Here we show evidence for the validity of both argumentations.

Detection criteria

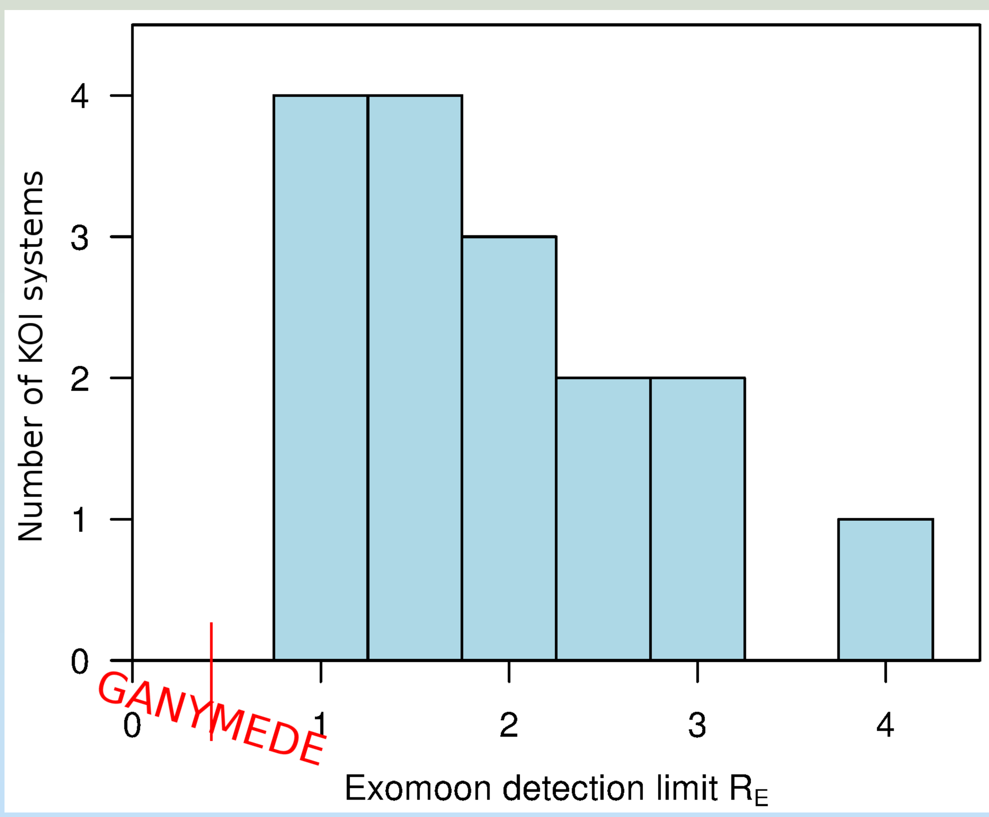
The moon affects the light curve in many ways: in transit timing, transit duration, light curve shape etc. These all can be elegantly handled via the momentums and central momentums of the lightcurve (the occulted light), which in accord of Szabó et al. 2012 are defined as

$$\mu'_n = \frac{\sum t_i^n \Delta m_i}{\sum \Delta m_i}, \quad \mu_n = \frac{\sum (t_i - \mu'_1)^n \Delta m_i}{\sum \Delta m_i}. \qquad (1)$$

The zeroth, first etc. momentums measure the transit depth, mean time, duration and higher order shape asymmetries as skewness, kurtosis etc. For a secure exomoon detection we required that both the photometric transit timing (PTV) and the skewness (SKEW)

$$PTV = \frac{\sum (t_i - \mu'_1)\Delta m_i}{\sum \Delta m_i}, \quad SKEW = \frac{\mu_3}{\mu_2^{1.5}} \qquad (2)$$

exceed the detection limit for a given KOI planet candidate, AND they refer to compatible exomoon parameters.
Our analysis has shown that for the most promising systems (offering a stable and securely detectable moon) exhibit detection limits in the 0.8–4 R_E size range. (The lower limit somewhat exceeds the smallest detected planets, but a moon transit is not a periodic process and the presence of a planet is a source of significant noise.)
These systems are capable of harbouring a stable exomoon with the given size, but they clearly don't. This finding suggests that moons around two times the Ganymede's size do not exist in the Universe. This is an intriguing consequence of exomoon surveys with *Kepler*, and it is worth a deeper debate to contrast with current moon formation theories.



Histogram of the detection limit for a moon around the Kepler candidates.

References

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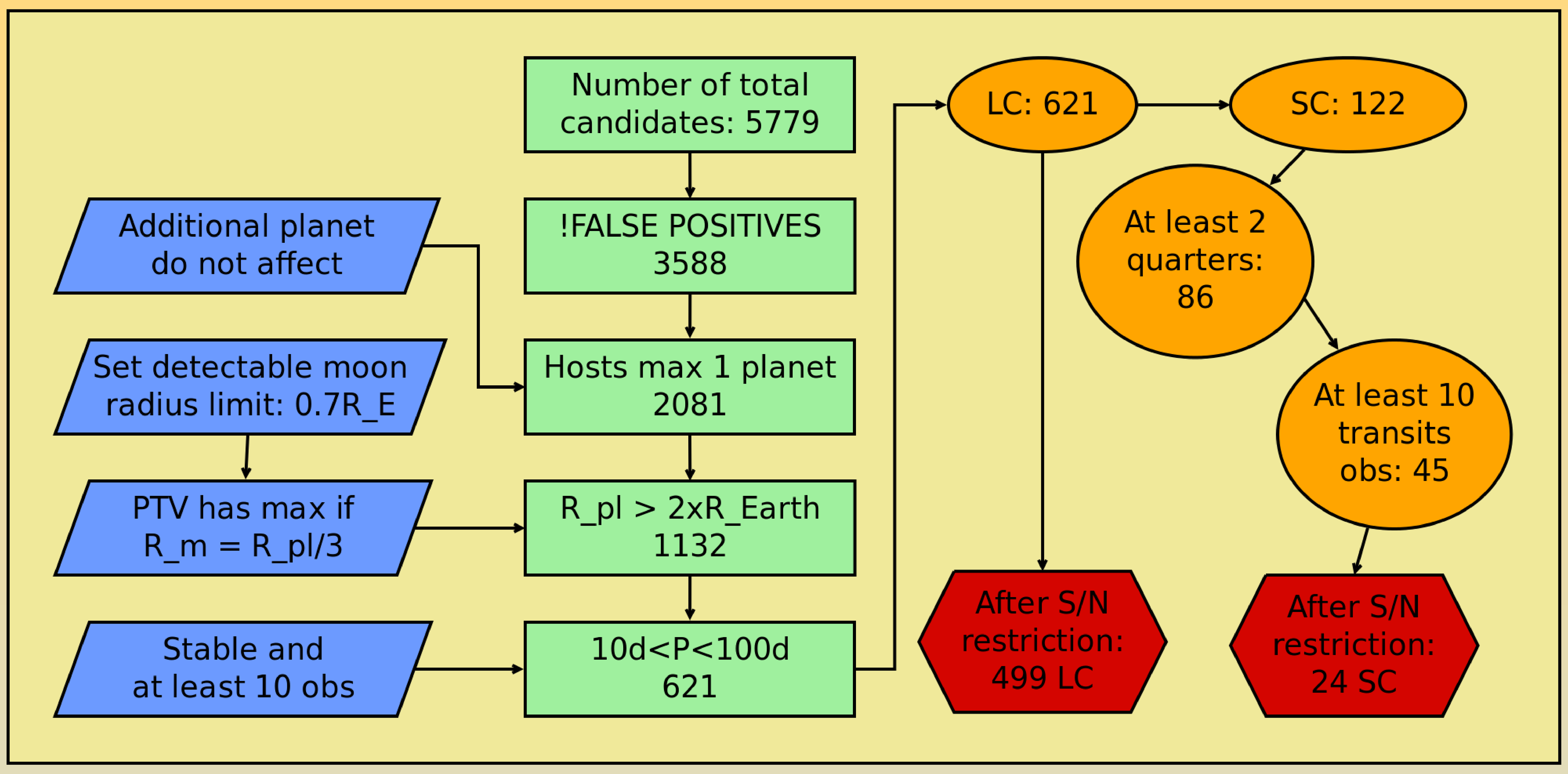
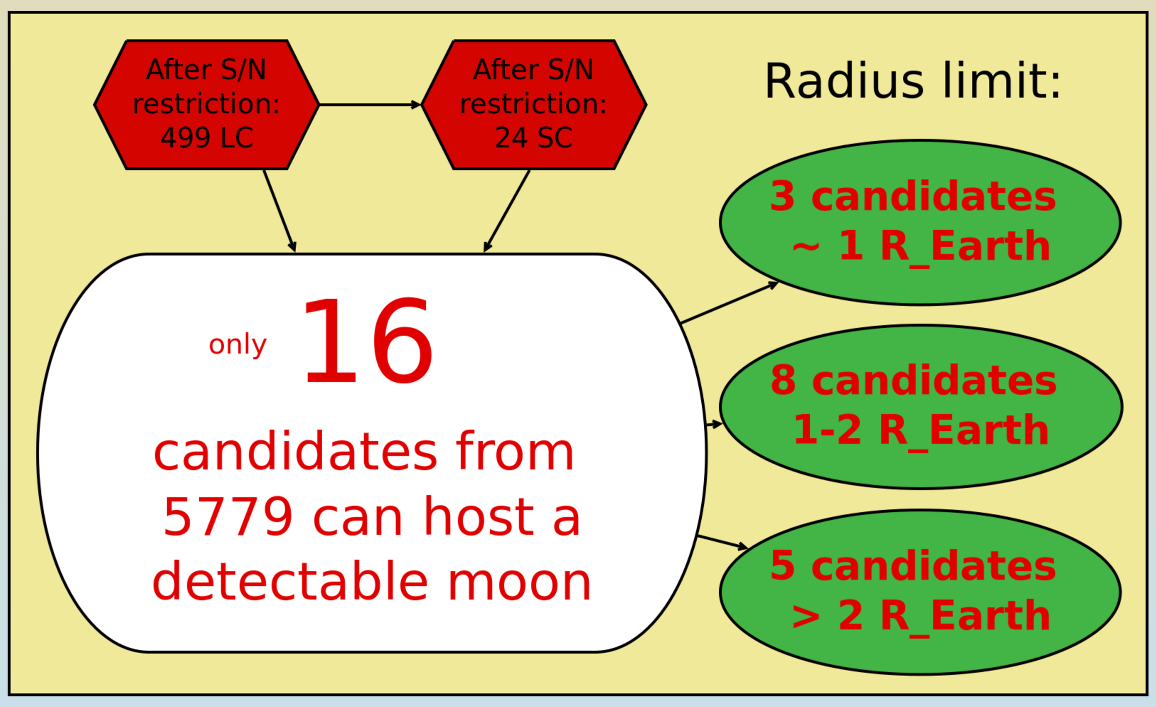
Data selection



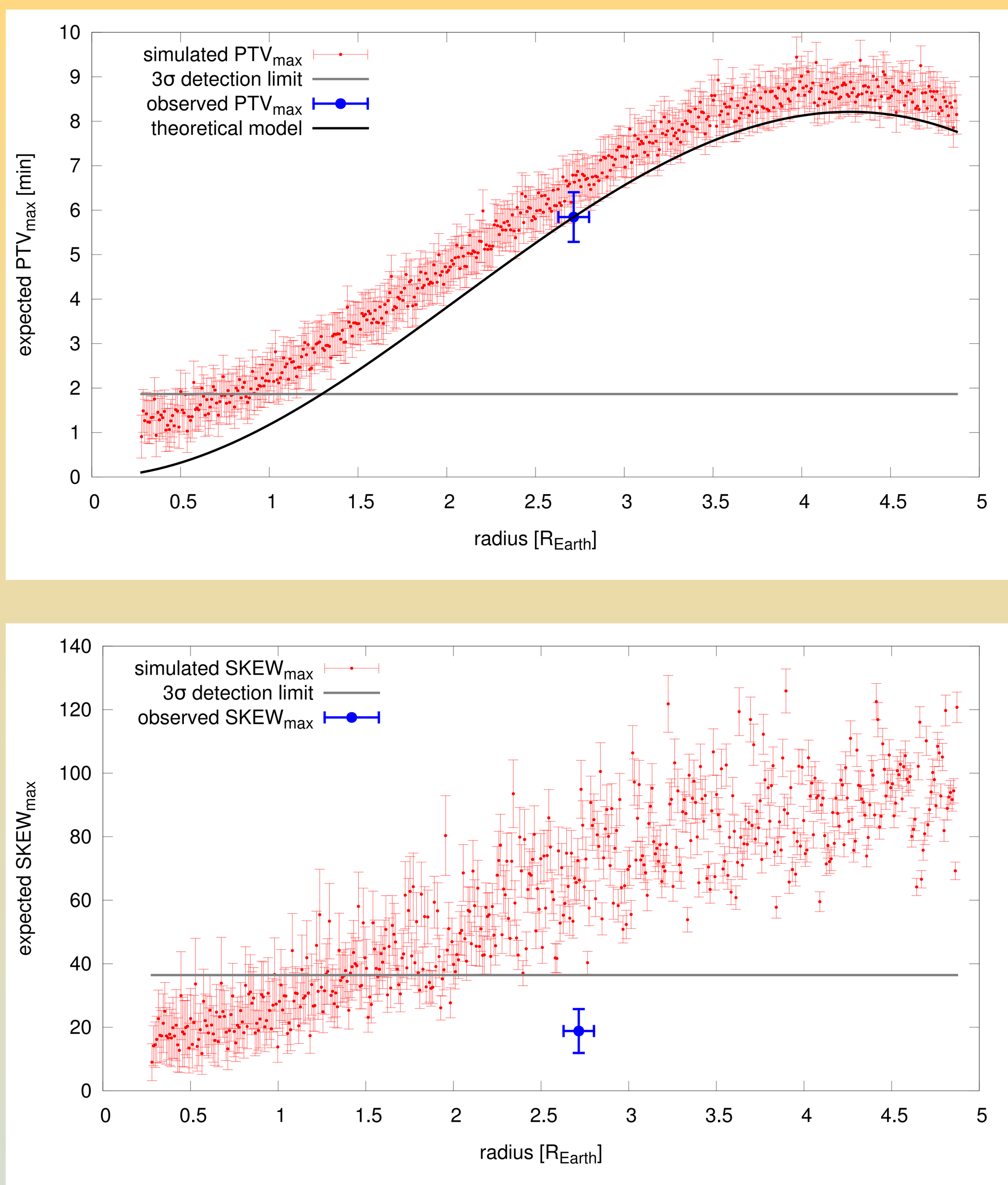
The flowchart of selection process. After selecting the candidates we analyzed 499 systems with long cadence (LC) data and among them only 24 systems have short cadence (SC) data. The properties of KOIs are from http://exoplanetarchive.ipac.caltech.edu

Data Selection. The list of KOIs at the NASA Exoplanet Archive was the base of our selection. We analyzed those candidates whose disposition were not FALSE POSITIVES and there were no additional planets in the systems. The studies of detectability of exomoons showed that we are able to detect Earth-sized moons with Kepler therefore we set this limit to $0.7R_{Earth}$. The signal of PTV reaches its maximum at $R_{moon} \approx R_{Earth}/3$ so we were seeking candidates above $2R_{Earth}$. Another limitation is that moons around planets can be stable on long timescale (a few billion years) if the host planets have orbital periods above 10 days (Barnes & O'Brien 2002), while the upper limit based on the number of observed transits during the Kepler mission. The candidates with SC data which have less than 10 observed transits or the observation time is shorter than 60 days (2 quarters) were ignored. Finally the transit depth of the largest probable moon must be higher than the photometric noise. At the end among the 499 LC candidates we have only 24 SC ones.



The result of the simulations shows that there are only 16 systems among the 5779 candidates which can host a moon that could be detected by the Kepler. This means that there are no moons around the candidates or their size are smaller than $R_{Earth}/3$.

(Un)detectable moon around Kepler candidates?



The expected (red points) and observed (blue crosses) photometric transit timing variation (upper panel) and skewness (lower panel) for a Kepler planetary candidate. The radius of an probable moon is derived from the theoretical model (gray curve, Szabo+ 2006). The black line shows the 3σ detection limit

Simulations. We performed a simulation for all candidates to determine the minimum radius of a theoretical moon that can be detected in the Kepler data. We used the data (epoch, period, duration, transit depth) of planetary candidates from the NASA Exoplanet Archive catalog to simulate real observation sets. These sets consisted of 500 runs with even larger moons ($0.2R_E - 1/3R_p$), the number of the simulated transits are equal to that of ones observed by the Kepler. In every simulation the planet–moon separation were maximized and from transit to transit the moon appeared in the opposite side of the planet (2:5 orbital period resonance).

Momentum analysis. All the central momentums were calculated for all transits and their maximum values from the "O–C" diagrams were taken in each run. These values are illustrated in the left panels with red points in the case of an example candidate and show how the PTV and skewness increase with larger moons. The 3σ detection limit was set using a bootstrapping method applied for 500 simulations without moon (gray lines). The magnitude of the expected PTV-effect (black curve) derived by Szabo et al. (2006) coincides nicely with our simulation (red points with 1σ error bars). The minimum radius for a detectable moon can be find where the expected value of PTV exceeds the detection limit. If this does not happen than there is no moon in the given system that can be detected by the Kepler space telescope.

An example. There were 16 planetary candidates (4 of them have SC data) among the 499 systems which can host a theoretically detectable moon. Three systems have a $\approx 1R_E$ detection limit, eight ones have $1R_E$–$2R_E$ and five ones have $R_E > 2$ (see the second flowchart and the histogram). The panels on the left show an example from the 16 candidates where the observed maximum value of the PTV is higher than the detection limit but SKEW variation is under the limit and lower than the expected one therefore these variations may not originate from the presence of an exomoon and the system needs to be studied more thoroughly.

Acknowledgements

This project has been supported by the Hungarian OTKA Grants K76816, K83790, K104607, the HUMAN MB08C 81013 grant of the MAG Zrt., KTIA URKUT_10-1-2011-0019, NSF PHY05-51164, the "Lendület-2009 Young Researchers" Program of the Hungarian Academy of Sciences and by the City of Szombathely under agreement No.S-11-1027. GyMSz and RSz were supported by the Janos Bolyai Research Fellowship of the Hungarian Academy of Sciences.