Statistical validation of PLATO 2.0 planet candidates

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Outline

• Planet Validation.

• Motivation in the context of PLATO 2.0

• The Planet Analysis and Small Transit Investigation Software (PASTIS).

• Testing PASTIS on synthetic data.

• The radial velocity contribution.
Planet Validation (alla BLENDER)

- Use all the information in the transit LC to constrain possible false positives (FPs).
- Add additional constrains from other datasets: RV, AO, multi-band photometry, ...
- Evaluate relative occurrence of planets to surviving blends (use Galactic models, current knowledge on mult. systems, etc.)

Fressin et al. (2011)
Planet Validation (the Bayesian way)

Model comparison: based on the computation of the odds ratio.

\[ O_{ij} = \frac{p(H_i|D, I)}{p(H_j|D, I)} = \frac{p(H_i|I)}{p(H_j|I)} \cdot \frac{p(D|H_i, I)}{p(D|H_j, I)} \]

- Hypotheses must be described by a model \( M \) with parameter vector \( \theta \).
- The Bayes’ factor is the ratio of the evidence for each model, defined as:

\[ p(D|H, I) \equiv p(D|M) = \int d\theta \, p(\theta|M) p(D|\theta, M) \]

- The evidence is a \( k \)-dimensional integral, generally intractable!
Motivation in the context of PLATO 2.0

• PLATO is expected to detect thousands of small-size planet candidates.

• Validation will be needed (unless reliance on Galactic priors is acceptable).

• RV confirmation is in principle be possible, but very time-demanding (see HARPS RV survey; talk by S. Udry). RV facilities likely limited to perform intense follow-up.

• Some stars will not be easily measured (fast rotators, hot stars, ...).

• High S/N of many candidates (e.g. S/N ~ 150 for a single Earth-size planet transit on 1-yr orbit around a mV = 8 star).

• Possible strategy: focus on validated planets to complete characterization (mass, eccentricity, bulk density, ...).
Planet Analysis and Small Transit Investigation Software

Rigorousness (fully-Bayesian approach)
Flexibility (in the definition of FP scenarios)
Speed (to be able to apply it to large samples)
The PASTIS data models

Light curves
(Kepler, CoRoT, Spitzer, ...)

Spectral Energy Distribution
(SDSS, 2MASS, WISE, ...)

Radial velocities
RV, Bisector, FWHM
(HARPS, SOPHIE)

Model priors
(Binary prop., planet prop., ...)

MCMC
Full parameter posterior

Bayes’ factor

\[ O_{ij} = \frac{p(H_i|D, I)}{p(H_j|D, I)} = \frac{p(H_i|I)}{p(H_j|I)} \cdot \frac{p(D|H_i, I)}{p(D|H_j, I)} \]

Full details in Díaz et al. (2013, in prep.)
Tests on synthetic data
Synthetic data

- Noise level near the median for SC targets of Q4.
- Planet transiting candidate. Already checked.
- For simplicity, just use light curve. In some cases the other observables dominates (cf. CoRoT-16, Ollivier et al. 2012).
Model **P**: “the signal is produced by a transiting extrasolar planet”.
Model **B**: “the signal is produced by a background eclipsing binary”.
+ data model: “jitter is an additional source of Gaussian error.”
Synthetic data

**Transiting Planets**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planet Radius $R_\oplus$</td>
<td>${1.0; 4.4; 7.8; 11.2}$</td>
</tr>
<tr>
<td>Impact Parameter $b$</td>
<td>${0.0; 0.5; 0.75}$</td>
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<tr>
<td>Transit S/N</td>
<td>${20; 50; 150; 500}$</td>
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Transit S/N independently varied from planet radius.

$b = 0.75$ near median of KOI distribution.

*S/N = 50; b = 0.5*
Synthetic data

Transiting Planets

Studied parameters

<table>
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<tr>
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Transit S/N independently varied from planet radius.

$b = 0.75$ near median of KOI distribution.
The synthetic signals were injected to the Kepler star KI target list. On the other hand, its located in the 6P magnitude bin. For stars in the same magnitude bin, the distribution for stars in the same magnitude bin is near the median of the Kepler short cadence mode distribution for stars in the same magnitude bin. Using the Kepler short cadence data for star KI, which were taken out before injecting the model light curves, we constructed the synthetic light curves to be analyzed with the method being described. The synthetic light curves were analyzed to test our method in different conditions of signal-to-noise ratio and to verify that the method is robust to different conditions of signal-to-noise ratio.

### Table 4. Parameters for synthetic light curves

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Transit S/N independently varied from planet radius. $b = 0.75$ near median of KOI distribution.
Results (I: PLANET simulations)

\[ b = 0.0 \]

\[ b = 0.50 \]

\[ b = 0.75 \]

\[ B_{10} < 3: \text{inconclusive evidence} \]

\[ 3 < B_{10} < 20: \text{positive evidence} \]

\[ 20 < B_{10} < 150: \text{strong evidence} \]

\[ B_{10} > 150: \text{very strong evidence} \]
Results (I: PLANET simulations)

\( b = 0.0 \)

\( b = 0.50 \)

\( b = 0.75 \)

- Monotonic decrease of \( B_{PB} \) with planet radius, and S/N of transit.
- Minimum \( B_{PB} \) for \( b = 0.5 \).
- For \( b = 0.75 \), highest value of \( B_{PB} \).
- S/N = 20 and 500 (not plotted) are completely inside and outside of shaded are, respectively.
Synthetic data

Background eclipsing binaries

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<tbody>
<tr>
<td>Background Eclipsing Binary</td>
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<tr>
<td>Mass Ratio</td>
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<td>Impact Parameter (b)</td>
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<td>Secondary S/N</td>
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Secondary S/N: a way to quantify the dilution provided by the foreground target star.
Results (II: BEB simulations)

- Monotonic increase of $B_{BP}$ with mass ratio $q$, snr of the secondary, and decrease with impact parameter.
- BEB model is not strongly chosen for highest dilution level at any $q$ or snr.
- Secondaries with snr = 7 lead to strong evidence for the BEB hypothesis (except $q = 0.1; b = 0.75$)
The radial velocity contribution

Could RV measurements help us decide on some cases?

- Velocity and bisector amplitudes are computed.

- Best-fit BEB model to PLANET simulations; RV amplitude clearly detectable.
Summary and Conclusions

- Planet validation is the only technique to establish the planetary nature of the smallest transiting candidates from CoRoT and Kepler.
- PASTIS correctly identifies both transiting planets and false positives if the signal is sufficiently high.
- Simulations of synthetic data show that BEB with a modest dilution are easily detectable as such. However, if the dilution is such that the secondary eclipse has signal-to-noise ratio ~ 2, the data cannot say much.
- For simulated PLANETS, only data from very-high-S/N transits provides strong support for the planet scenario.
- For the unresolved cases, the model priors will be the deciding factor. Other observations: AO, etc.
- Radial velocities can contribute in this point. Apparently more so in the case of planets than BEBs.