Minimising the needs of follow-up observations for PLATO

- the central role of planet-validation tools -

Alexandre Santerne
*Marie Curie Fellow*
Instituto de Astrofísica e Ciências do Espaço
Universidade do Porto
alexandre.santerne@astro.up.pt

supported by the European Union under a Marie Curie Intra-European Fellowship for Career Development with reference FP7-PEOPLE-2013-IEF, number 627202.
The planet-validation technique, in short

Almenara et al. (2011)
The planet-validation technique, in short

1. Model all astrophysical false-positive scenarios
2. Constrain scenarios using available data
3. Evaluate each scenario probability

\[
O_{ij} = \frac{\pi(S_i | I) \cdot \int_{\theta_i} \pi(\theta_i | S_i, I) \cdot \mathcal{P}(D | \theta_i, S_i, I) \, d\theta_i}{\pi(S_j | I) \cdot \int_{\theta_j} \pi(\theta_j | S_j, I) \cdot \mathcal{P}(D | \theta_j, S_j, I) \, d\theta_j}
\]

Almenara et al. (2011)
The planet-validation technique, in short

Figure 2: Density map of stars in the background of Kepler-20.

The blue-shaded contours correspond to main-sequence star counts from the Besançon Galactic Model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

The data was detrended and phase-folded at the period of the two transits. Transit models (red curves) smoothed to the 29.426-min cadence are overplotted. These two signals are unambiguously detected in each of the eight quarters of Kepler data, and have respective signal-to-noise ratios of 23.6 and 18.5, which cannot be due to stellar variability, data treatment or aliases from the other transit signals.

Fressin et al. (2012)
The planet-validation technique, in short

used for this work were gathered between 13 May 2009 and 14 March 2011 (quarter 1 to quarter 8), and comprise 29,595 measurements at a cadence of 29.426 min (black dots). The Kepler photometry phase-binned in 30-min intervals (blue dots with 1 standard error of the mean (s.e.m.) error bars) for Kepler-20 e (a) and Kepler-20 f (b) is displayed as a function of time, with the data detrended and phase-folded at the period of the two transits. Transit models (red curves) smoothed to the 29.426-min cadence are overplotted. These two signals are unambiguously detected in each of the eight quarters of Kepler data, and have respective signal-to-noise ratios of 23.6 and 18.5, which cannot be due to stellar variability, data treatment or aliases from the other transit signals.

Figure 2 Density map of stars in the background of Kepler-20.

The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

Besançon Galactic Model

data constraints

Probability of each astrophysical scenario

Fressin et al. (2012)
The planet-validation technique, in short

If the planet scenario is significantly the most likely scenario

→ validated planet
PASTIS:
Planet Analysis and Small Transit Investigation Software

Data and constraints
- **Radial velocities:**
  - SOPHIE, HARPS, HARPS-N, etc...
- **Spectral Energy Distribution:**
  - SDSS, 2MASS, WISE, etc...
- **External constraints:**
  - Stellar atmospheric parameters (Teff, logg, [Fe/H]), Asteroseismic constraints (p), etc...

Other inputs
- **Prior distribution**

Outputs
- **System parameter values and robust uncertainties**
- **Probability of astrophysical scenario**

Planet Analysis & Small Transit Investigation Software

Embedded models
- **Light-curve model:**
  - EBOP + beaming
- **LD coefficients:**
  - Claret & Bloemen (2011)
- **Stellar evolution models:**
  - Dartmouth, Parsec, Geneva, StarEvol
- **Stellar atmosphere models:**
  - ATLAS/Castelli & Kurucz, PHOENIX/BT-SETTL
- **Rossiter-McLaughlin effect:**
  - Arome, SOAP-T
- **Stellar activity models:**
  - SOAP/SOAP-T, Macula
- **Dynamical model:**
  - Mercury6
- **Galactic extinction model:**
  - Amôres & Lépine (2005)

Astrophysical objects
- **Planet**
- **Star**
- **Blended star**
- **Planetary systems**
- **Binary**
- **Multiple system**
  - Triple, Planet in binary, etc...

Santerne, Díaz, Almenara, et al., 2015, in prep.
**PASTIS:**
Planetary Analysis and Small Transit Investigation Software

In numbers:
- Python (v2.7) code with C++, fortran, and IDL routines
- ~23 000 lines of code
- eq. ~3x full-time PhD / post-doc for 3 years (2010 - now)
- Computation time needed (4yrs of *Kepler* data):
  - 1k - 5k CPU hours (planet analysis)
  - 5k - 25k CPU hours (validation)
Today’s view of PLATO follow-up, step by step

- **Lightcurve vetting**
  - period & depth?
  - duration
  - shape? ingress-egress time?
  - out-of-transit variations?

- **Spectroscopic Reconnaissance**
  - no CCF (hot star, high vsini)
  - binaries

- **High-angular resolution image**
  - eliminate blend scenarios ➔ Photometric follow-up

- **Precise radial velocities:**
  - steps with increasing precision
  - adapted to star characteristics

- **False positives**
  - intrinsic variations
  - transit by WD
  - blends
    - triples
    - giant planets transits

- **No characterization**
  - hot stars
  - high rotation
  - active stars
  - other

- **Confirmed planets**
  - mass, radius, density
  - orbital parameters
  - host star characteristics
  - science follow-up

Validation only planned on RV-boring stars*

*RV-boring stars: stars not suitable for precise RV observations, thus not suitable for precise planet mass determination
Planet-validation tools: optimising the follow-up of PLATO

PLATO products:
- LC, Δα, Δδ, Δν

GAIA products:
- π, L, Av, BG ☆ density

Other data:
- Spectra, RVs, ...

1. Define the parameter space compatible with the PLATO data for all scenarios
2. Define which follow-up observation is the most efficient to further constrain them

Compute probability of each scenario
- Bound
- Unbound
Example of how to optimise the follow-up of PLATO with PASTIS

used for this work were gathered between 13 May 2009 and 14 March 2011 (quarter 1 to quarter 8), and comprise 29,595 measurements at a cadence of 29.426 min (black dots). The Kepler photometry phase-binned in 30-min intervals (blue dots with 1 standard error of the mean (s.e.m.) error bars) for Kepler-20e (a) and Kepler-20f (b) is displayed as a function of time, with the data detrended and phase-folded at the period of the two transits. Transit models (red curves) smoothed to the 29.426-min cadence are overplotted. These two signals are unambiguously detected in each of the eight quarters of Kepler data, and have respective signal-to-noise ratios of 23.6 and 18.5, which cannot be due to stellar variability, data treatment or aliases from the other transit signals.4

Figure 2
Density map of stars in the background of Kepler-20.
The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).
Example of how to optimise the follow-up of PLATO with PASTIS

Figure 2

Density map of stars in the background of Kepler-20.

The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

Kepler-20e

Fressin et al. (2012)
Example of how to optimise the follow-up of PLATO with PASTIS

Figure 2

Density map of stars in the background of Kepler-20.

The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

Kepler-20e
Fressin et al. (2012)
Example of how to optimise the follow-up of PLATO with PASTIS

used for this work were gathered between 13 May 2009 and 14 March 2011 (quarter 1 to quarter 8), and comprise 29,595 measurements at a cadence of 29.426 min (black dots). The Kepler photometry phase-binned in 30-min intervals (blue dots with 1σ standard error of the mean (s.e.m.) error bars) for Kepler-20e (a) and Kepler-20f (b) is displayed as a function of time, with the data detrended and phase-folded at the period of the two transits. Transit models (red curves) smoothed to the 29.426-min cadence are overplotted. These two signals are unambiguously detected in each of the eight quarters of Kepler data, and have respective signal-to-noise ratios of 23.6 and 18.5, which cannot be due to stellar variability, data treatment or aliases from the other transit signals.

Figure 2 Density map of stars in the background of Kepler-20. The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

Kepler-20e
Fressin et al. (2012)
Example of how to optimise the follow-up of PLATO with PASTIS

Used for this work were gathered between 13 May 2009 and 14 March 2011 (quarter 1 to quarter 8), and comprise 29,595 measurements at a cadence of 29.426 min (black dots). The Kepler photometry phase-binned in 30-min intervals (blue dots with 1 V standard error of the mean (s.e.m.) error bars) for Kepler-20e (a) and Kepler-20f (b) is displayed as a function of time, with the data detrended and phase-folded at the period of the two transits. Transit models (red curves) smoothed to the 29.426-min cadence are overplotted. These two signals are unambiguously detected in each of the eight quarters of Kepler data, and have respective signal-to-noise ratios of 23.6 and 18.5, which cannot be due to stellar variability, data treatment or aliases from the other transit signals.

Figure 2 Density map of stars in the background of Kepler-20. The blue-shaded contours correspond to main-sequence star counts from the Besançon model in the vicinity of Kepler-20, as a function of stellar mass and magnitude difference in the Kepler passband compared to Kepler-20. The red-shaded contours represent the fractions of those stars orbited by another smaller star (a and c) or by a planet (b and d).

Only SPHERE is relevant to constrain this scenario. Both HARPS and SPHERE might be useful to constrain this scenario.
Role of planet-validation tool in PLATO

- The PASTIS planet-validation tool could evaluate the probability of all astrophysical scenarios and constrain their parameters.
Role of planet-validation tool in PLATO

- The PASTIS planet-validation tool could evaluate the probability of all astrophysical scenarios and constrain their parameters.

- These constraints could be used to define the best follow-up strategy to rule out the false positives and secure the planet detection.
Role of planet-validation tool in PLATO

• The PASTIS planet-validation tool could evaluate the probability of all astrophysical scenarios and constrain their parameters.

• These constraints could be used to define the best follow-up strategy to rule out the false positives and secure the planet detection.

• Then, it would be possible to quantify the probability of a given observation / given instrumentation to detect a false-positive scenario, if the candidate is not a planet.
Limitations of planet-validation tools

- CPU-intensive
- Need reduced light-curves (no stellar activity, no TTVs, no instrumental effects) otherwise it takes even more time.
- More efficient with GAIA products, stellar mean density from asteroseismology, complete list of BG contaminants (PIC-CC)
Limitations of planet-validation tools

- CPU-intensive

- Need reduced light-curves (no stellar activity, no TTVs, no instrumental effects) otherwise it takes even more time.

- More efficient with GAIA products, stellar mean density from asteroseismology, complete list of BG contaminants (PIC-CC)

→ Could be used at least on the most expensive candidates + “RV-boring stars”
To-Do list (for the next 4-9.1 years)

• Improve & fasten the code (some ideas - on going)

• Make it more automatic

• Include more observable (e.g. centroids)

• Characterise the follow-up instruments [WG 14x]

• Define priorities [WG 113]
The role of amateur astronomers:
even decrease (professional) telescope time

Possible role of amateurs:
• screen out EBs
• characterise giant planets
• characterise EB of CBP

Amateurs have almost unlimited access of telescope time

2m telescope + ELODIE

27cm telescope + home-made R=50k spectro
Take-home messages

• Planet-validation tools like PASTIS could optimise the follow-up observations

• CPU-time consuming

  ➔ unlikely to be applied to all POIs (PLATO Objects of Interest)

  ➔ could be applied only to the most expensive planets (small & cool planets)

• Amateur astronomers could also participate substantially to the (RV) follow-up efforts.