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PASTIS: PLANETARY ANALYSIS AND SMALL TRANSIT INVESTIGATION SOFTWARE

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Abstract. The Transit search method to detect exoplanets is contaminated by *false positives*, produced by one of several kinds of configurations involving eclipsing binaries. Follow-up observations are used to reveal the true nature of the candidates. These observational efforts run into difficulties due, on one hand, to the faintness of the typical targets (specially for CoRoT and Kepler candidates), and on the other, due to the small-amplitude signals produced by small-mass planets. As a consequence many small planet candidates remain unsolved. We are developing a tool, called PASTIS, to solve these cases using all the available data including the light curve, photometry, radial velocity data, etc. We use bayesian methods to fit the data with different models and to compare and quantify the relative probability of different scenarios. In this way we plan to validate most of the currently unsolved cases and to increase the number of confirmed small planets.

Keywords: Planetary systems

1 Introduction

Several configurations of eclipsing binaries can produce eclipses that can mimick transits of exoplanets (see Fig. 1). There are two main kinds of *false positives*: 1) undiluted binaries, with grazing eclipses or large radius ratio, and 2) diluted binaries, eclipsing binaries whose light is diluted by a third star, physically bounded (triple system) or aligned with the line of sight of the binary, called blend. A careful inspection of the detection light curve (Alonso et al. 2004) permits identifying some *false positives.* For the ones that pass this inspection, follow-up observations are needed to confirm the planetary nature. Due to the large point-spread-function in the transit searches, eclipsing binaries contaminating the aperture are a major problem, which can be minimized using high spatial resolution observations or measurement of the photometric centroid (Batalha et al. 2010). Finally, the radial velocity observations allow obtaining the mass. However, with the current space-based transit searches, CoRoT (Baglin et al. 2009) and Kepler (Borucki et al. 2010), some candidates are too faint for spectroscopic follow-up, or the expected signals are below the current spectrographs precision, due to the small radial-velocity amplitudes produced by small-mass planets. In these cases the direct confirmation is not possible, but the candidate can still be validated as a real planet, if the probabilities greatly favor the planetary scenario over the *false positive* one. Some Kepler planets were validated using BLENDER (Torres et al. 2004, 2011; Fressin et al. 2011).

2 BLENDER

BLENDER compares models of different scenarios (star with a transiting planet, star with a background/foreground eclipsing binary, star with a background/foreground star with a transiting planet, star-eclipsing binary in a triple system or star-star-planet triple system) with Kepler light curve observations. The models assume the main star observed with fixed parameters and a blend object with 4-5 free parameters that depend on the scenario: masses for stars, radii for transiting planets, distance if its a background/foreground system, and a parameter related with the eccentricity. In the case of stars, the physical parameters are taken from an isochrone for a fixed age and metallicity. BLENDER explores the full set of parameters sampled in a regular

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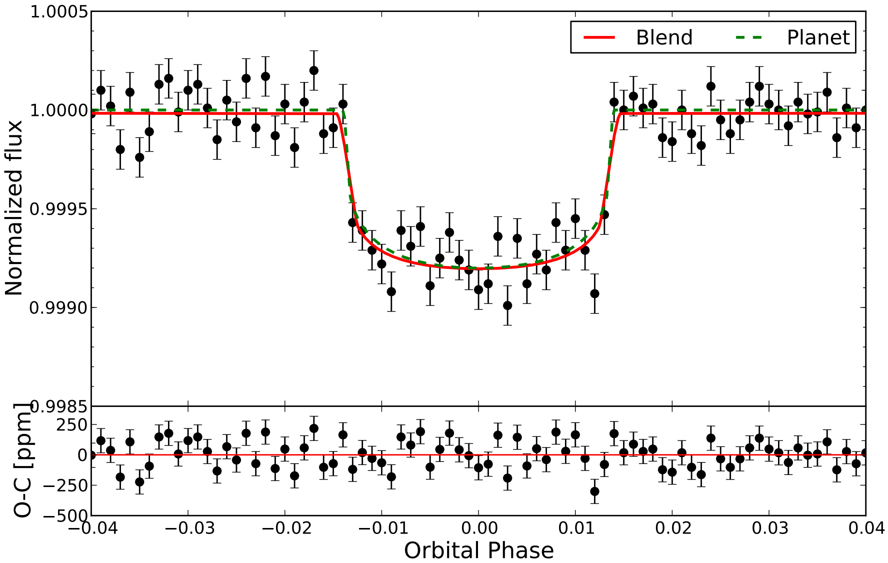

Fig. 1. A synthetic transit light curve generated from a planetary model, shown in green. The red curve is the best fit using a blend model. Both models are compatible with the data points (black dots with error bars).

grid. This process requires intensive computation resources (to compute up to 7×10^8 models), they use 1024 processors of the NASA Pleiades cluster. Then, they construct maps for two of the free parameters. The statistics in these maps is based on a χ^2 difference between the considered scenario and the best model of the star-transiting planet scenario. The confidence regions are obtained using the number of free parameters as the number of degrees of freedom, and the region outside the 3σ contour is excluded. But the general approach is not conceptually correct, as in the frequentist approach, model comparison is not possible (Gregory 2005). Moreover, this method has not been proved to be statistically consistent using, for example, simulated data. Additional observations (radial velocity, high resolution image with adaptive optics, transits observed in the infrared with Spitzer) add, a posteriori, constraints in the statistic maps produced from the χ^2 difference. These maps are used to constrain the allowed magnitude range of the blended stars (inside the 3σ contour and allowed by the additional observations). Then, they use the Besançon Galactic structure models (Robin et al. 2003) to count background/foreground stars in the allowed magnitude range. Finally, taking into account the star counts and the probability of each scenario they compute a false alarm rate for the star-transiting planet scenario. If this false alarm rate is small enough, the planet is said to be validated (Fressin et al. 2011).

Although the method is promising and has produced interesting results, no rigorous demonstration of its validity has been presented. We decided to develop our own validation code, called PASTIS, using an entirely bayesian approach that allows for statistically rigorous model comparison. Hopefully, this tool will permit confirming the Kepler validated planets and discover many more small transits in the CoRoT and Kepler candidate list.

3 PASTIS

PASTIS (Planetary Analysis and Small Transit Investigation Software) was conceived as a fully bayesian code that includes all the observations for the model comparison: light curves in different filters, radial velocity observations and photometric magnitudes in various filters, and is flexible to include new observables due to its modular structure. PASTIS models the light curve in a given filter using the JKTEBOP code (Southworth et al. 2004), based on the EBOP code (Popper & Etzel 1981; Etzel 1981; Nelson & Davis 1972), elipsoidal and reflection effect are included in the model. PASTIS analyze the radial velocity measurements (including bisector, full width at half maximum and constrast) from a simulated cross-correlation function (Díaz et al. 2012). Also, PASTIS models the spectral energy distribution to compare with the photometric magnitudes measurements. To generate these models, PASTIS use models of stellar atmospheres: ATLAS9 (Castelli & Kurucz 2004) or BT-Settl/Phoenix (Castelli & Kurucz 2004; Allard et al. 2007), stellar evolution tracks: Dartmouth (Dotter et al. 2008), *STAREVOL* (Palacios, *priv. com.*), Geneve (Mowlavi et al. 2012), COND (Baraffe et al. 2003);

limb darkening coefficients (Claret & Bloemen 2011), and galactic interstellar extinction (Amôres & Lépine 2005).

PASTIS uses a Markov Chain Monte Carlo (MCMC) algorithm to explore parameter space (Tegmark et al. 2004; Ford 2005, 2006). In this way the number of free parameters is not limited by the computational capabilities, since parameter space is explored efficiently. Principal components analysis decomposition (PCA) is used to minimize the effect of correlation between parameters (see Fig. 2), and guarantee a correct estimation of the confidence regions for all parameters.

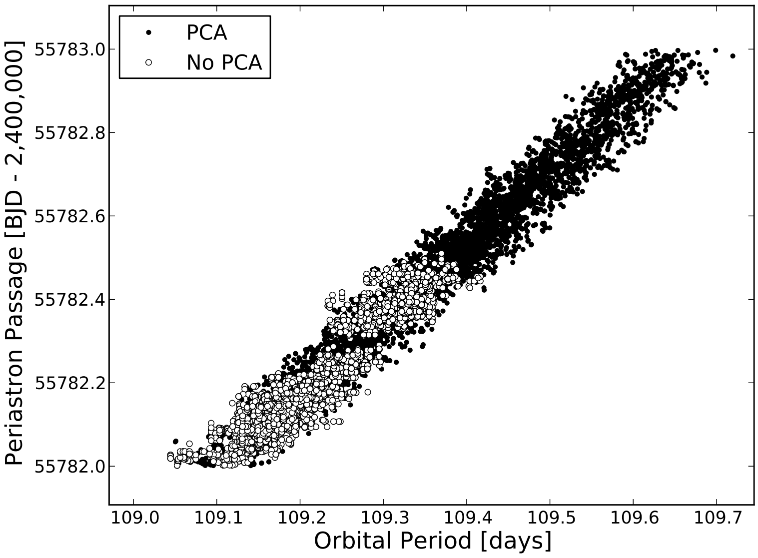

Fig. 2. The risk of correlations in MCMC. Correlated parameters (orbital period and periastron passage in this case) can effectively reduce the region parameter space explored by the chain. When PCA is used, linear correlations are not an impediment for the chain to move freely.

PASTIS is a python object-based code that provides a great flexibility in the definition of the scenarios: almost all possible conceivable false positive scenarios can be modeled using the same structure, and the odds ratio between each pair of models can be computed.

The comparison between scenarios should be made between two of them. Given two scenarios i and j, with its correspondant models M_i and M_j, the set of data D, the relative likelihood is given by:

$$O_{ij} = \frac{p\,(M_i|D,I)}{p\,(M_j|D,I)} = \frac{p\,(M_i|I)\,p\,(D|M_i,I)}{p\,(M_j|I)\,p\,(D|M_j,I)} \tag{3.1}$$

where $p\,(M_i|I)$ is the prior of the scenario i, and $p\,(D|M_i,I)$ is the global likelihood or evidence of the scenario i, and the same for j (Gregory 2005). Fig. 3 shows an example of this method. A synthetic diluted eclipsing binary light curve is fitted with a planetary model. From simple inspection of the residuals it is clear that the fit is poor: the ingress and egress times are too long to accommodate a planetary model. In this case, the ratio of global likelihoods will strongly (over 60 orders of magnitude) favor the blend scenario, and will allow to discard a planetary transit.

Additionally, PASTIS can be used just to fit a transiting planet or a binary (Santerne et al. 2012), and obtain rigorous confidence intervals for all parameters by using the MCMC algorithm.

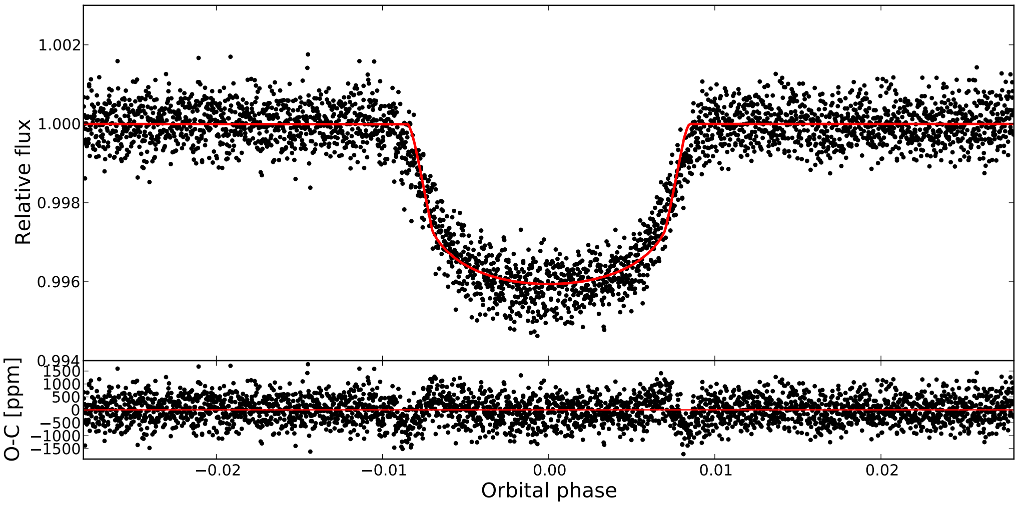

Fig. 3. Results of fitting a synthetic light curve of a diluted eclipsing binary with a planetary model. The fit is clearly poor: the ingress and egress are too long to accommodate a planetary model. In this case the ratio of global likelihoods strongly favors the *false positive* hypothesis.

References

Allard, F., Allard, N. F., Homeier, D., et al. 2007, A&A, 474, L21

Alonso, R., Deeg, H. J., Brown, T. M., & Belmonte, J. A. 2004, in ESA Special Publication, Vol. 538, Stellar Structure and Habitable Planet Finding, ed. F. Favata, S. Aigrain, & A. Wilson, 255

Amôres, E. B. & Lépine, J. R. D. 2005, AJ, 130, 659

Baglin, A., Auvergne, M., Barge, P., et al. 2009, in IAU Symposium, Vol. 253, IAU Symposium, 71

Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701

Batalha, N. M., Rowe, J. F., Gilliland, R. L., et al. 2010, ApJ, 713, L103

Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977

Castelli, F. & Kurucz, R. L. 2004, ArXiv Astrophysics e-prints

Claret, A. & Bloemen, S. 2011, A&A, 529, A75

Díaz, R. F., Santerne, A., Sahlmann, J., et al. 2012, A&A, 538, A113

Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, ApJS, 178, 89

Etzel, P. B. 1981, in Photometric and Spectroscopic Binary Systems, ed. E. B. Carling & Z. Kopal, 111

Ford, E. B. 2005, in Protostars and Planets V, 8358

Ford, E. B. 2006, ApJ, 642, 505

Fressin, F., Torres, G., Désert, J.-M., et al. 2011, ApJS, 197, 5

Gregory, P. C. 2005, Bayesian Logical Data Analysis for the Physical Sciences: A Comparative Approach with 'Mathematica' Support

Mowlavi, N., Eggenberger, P., Meynet, G., et al. 2012, A&A, 541, A41

Nelson, B. & Davis, W. D. 1972, ApJ, 174, 617

Popper, D. M. & Etzel, P. B. 1981, AJ, 86, 102

Robin, A. C., Reylé, C., Derrière, S., & Picaud, S. 2003, A&A, 409, 523

Santerne, A., Díaz, R. F., Moutou, C., et al. 2012, A&A, 545, A76

Southworth, J., Maxted, P. F. L., & Smalley, B. 2004, MNRAS, 351, 1277

Tegmark, M., Strauss, M. A., Blanton, M. R., et al. 2004, Phys. Rev. D, 69, 103501

Torres, G., Fressin, F., Batalha, N. M., et al. 2011, ApJ, 727, 24

Torres, G., Konacki, M., Sasselov, D. D., & Jha, S. 2004, ApJ, 614, 979