Precise photometric timming of transiting exoplanets

Proposal for the spanish network of robotic telescopes

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ABSTRACT

Some general aspects on photometric timming of eclipsing systems and transiting exoplanets are discussed. The aim is to motivate the discussion with the responsible groups of the robotic facilities in the spanish community in order to implement an intensive follow-up program of transiting exoplanets for timming purposes.

Key words. Exoplanets – Binaries – Photometry – Astrometry – Reference Systems

1. Proposal

In a planetary system with more than one planet, the gravitational interactions between the components produce to short term orbital perturbations. If one planet is transiting, the instant of central transit is very sensitive to such orbital perturbations leading to the so-called transit timming variations(TTV). The effect is discussed in great detail in Agol et al. (2005), where the authors claim that terrestrial mass planets can be detected by this method.

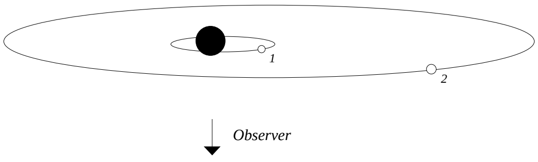

Fig. 1. Schematic representation of the potential system to be studied

The accumulated effect can be observed by the traditional O-C technique from some derived linear ephemeris (see Fig. 2). The figures presented here are obtained introducing a second planet of 1 Jupiter mass to the HD209458 with an orbital period of 28 days and $e = 0.3$. The TTV amplitude is difficult to predict analytically since particular orbital configurations, such as resonances, can power-up the effect (Steffen & Agol, 2005). In Holman & Murray (2005) the time interval between two consecutive transits

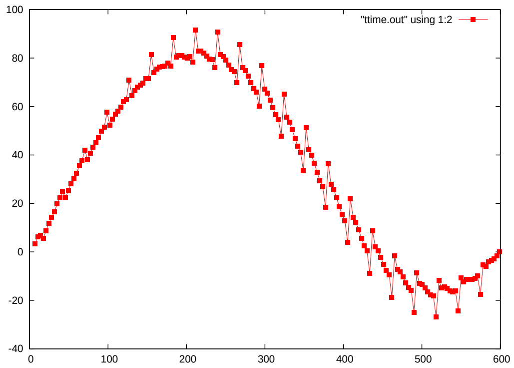

Fig. 2. Accumulated TTV effect. The X axis is the transit number from a given epoch and the vertical axis is the observed discrepancy with respect to the expected transit instant. Such O-C diagram should not be confused with the standard light travel-time effect which is not included here and should have an amplitude of a fraction of a second.

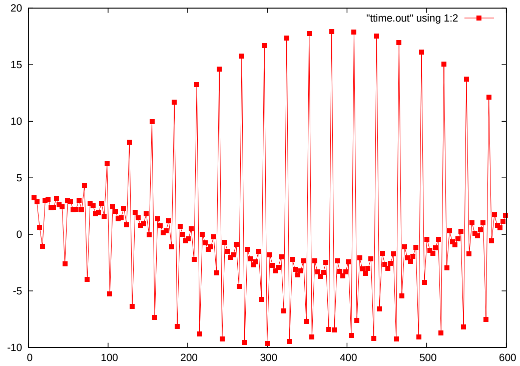

Fig. 3. Transit–to–transit interval variation. The the transit–to–transit interval variations are easier to predict analytically but the amplitudes are only of a few seconds and are very difficult to measure.

is discused since this quantity permits a better analysis(see Fig. 3). They show that the TTV amplitude is usually proportional to the orbital period of the transiting planet. Unfortunately, only transiting exoplanets with very short periods are known up to the date.

Systematic obtention of light curves of transiting planets is a hard bussiness. Apart from the required photometric accuracy (at mmag level) only a few nights during the year permit to obtain the whole transit for a given object since they have typical durations of 3-4 hours. In order to achieve useful accuracy a reasonable number of photometric points during the ingress/egress (points with maximal slope) with precise photometric measurements are required. All these accuracy aspects are discussed in Sec. 2.

In order to reduce the requirements on the telescope time, it should be considered to observe only the ingress and the egress parts of the eclipses (one hour of observations per transit should do the job in most cases). Given the current small number of detected transiting exoplanets, this implies a dedication of a few hours per month (i.e. 12 hours). For some reasons, most of the transiting planets can be better (or only) observed during the Autums/Winter semester. Only a couple of them can be observed during Spring/Summer.

This situation may change in brief with the data release of the COROT mission and the ongoing planet finding projects by the method of transit (WASP, XO, HAT, STARE, etc). New transiting exoplanets with long orbital periods should be carefully monitored with high priority when available.

2. Timming accuracy

A light curve is given by a collection of pairs F_i, t_i with their individual formal errors σ_i assumed gaussian,

$$\begin{aligned} \boldsymbol{t} &= [t_1, t_2, \dots t_i, t_{i+1}, \dots, t_N] \;, & (1) \\ \boldsymbol{F} &= [F_1, F_2, \dots F_i, F_{i+1}, \dots, F_N] \;, & (2) \\ \boldsymbol{\sigma} &= [\sigma_1, \sigma_2, \dots \sigma_i, \sigma_{i+1}, \dots \sigma_N] \;. & (3) \end{aligned}$$

Let us assume that a model for the shape of the minima is given as a function $f(t)$. Then, the best case accuracy in the instant of transit estimation obtained from a least square matching of the observational data with the model function is given by

$$\sigma_T > \left(\sum_j \frac{1}{\sigma_j^2} \left. \frac{\partial f}{\partial t} \right|_{t_j}^2 \right)^{-1/2} \qquad (4)$$

This expression only depends on the slope f' of the light curve. Points with no slope do not contribute to the instant of transit estimation. Paradoxically this excludes the point of the minima itself. This comment is also valid for light curves with flat minimas (i.e. transiting exoplanets, see Fig. 4). Only the ingress and egress parts of the light curves should be used for precise timing purposes.

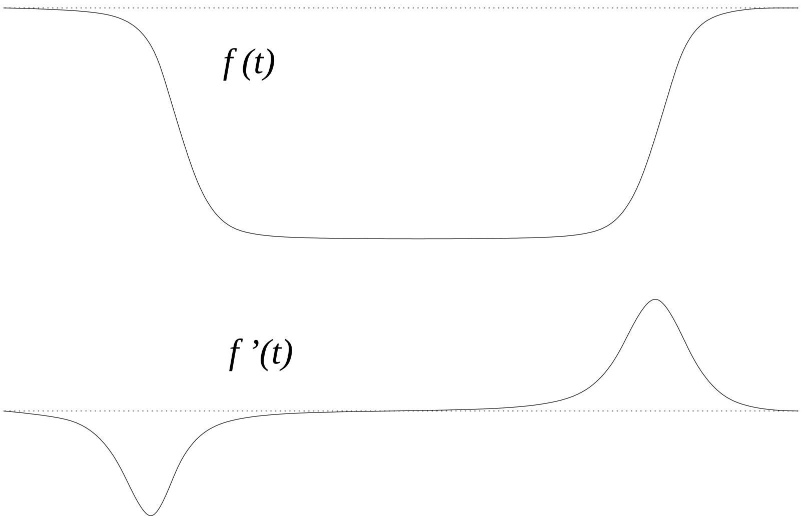

Fig. 4. Only the parts with a significative slope do contribute to the instant of transit estimation. This is the typical shape of the light curve obtained during a planetary transit.

2.1. A minimum with constant slope

Let us apply (4) to the most simple example. Assume that there is a source that has a light curve with constant slopes (see Fig. 5 given by

$$f\,[t] \;=\; -\frac{2\Delta F}{\tau}|t-T| \qquad \frac{-\tau}{2} < t-T < \frac{+\tau}{2} \tag{5}$$

$$\sigma_i \;=\; \epsilon_0 \tag{6}$$

where ΔF is the deepness of the eclipse in the same units as the photometric noise $\sigma_j \;=\; \epsilon_0$ which is constant, τ is the eclipse duration, t is the time coordinate and T is the instant of transit. After a few algebra it is obtained that

$$\sigma_T = \frac{\epsilon_0}{\sqrt{N}}\frac{\tau}{2\Delta F} \tag{7}$$

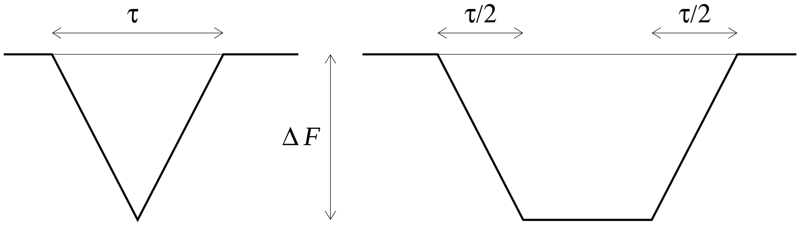

Fig. 5. Schematic light curves with constant slopes. The left figure aproximately corresponds to the case of an eclipsing system, while the right one is the typical profile of a transiting exoplanet. On the case of the transiting exoplanet, only the point with relevant slope are relevant.

where this expression provides the best possible accuracy given by such light curve. Abrupt and deep transits provide a better accuracy, as naively expected. An estimation of the accuracy that can be reached for transiting exoplanets observable from the northern hemisphere are given in Tab. 1.

A small number of low mass eclipsing binaries can also be monitored for light travel time effects in order to detect substellar companions with similar photometry requirements.

3. Instrument requirements and related issues

The main constrain is the obtention of good photometry with a reasonable rate, say $1mmag$ per minute. Several aspects must be considered when planning the observations with a given instrument

- Depending on the instrument and the observatory site, very short exposures for bright stars do not help to improve the photometry due to athmospheric scintillation, readout and shutter noise. Since such stars saturate the detector very fast, the usage of a narrow band filter should be considered.
- For bright objects, a star of comparable brightness in the same field of view is highly recommended. The quality of the photometry will be limited by the fainter reference star.
- For small apperture telescopes ($d \leq 0.5$ m) white light (no filter) may be considered for faint ($V \geq 11.0$) objects
- Large CCD arrays have long readout times. The use of windows and binned images can help to solve this problem.

Planet	V star (mag)	P (days)	Depth (mmag)	τ (min)	σ (s)
HD189733b	7.6	2.21	30	110	11
HD149026b	8.2	2.87	3	40	63
HD209458b	7.6	3.52	17	200	25
TrES-1	11.8	3.03	20	40	10
TrES-2	11.4	2.5	20	200	21
WASP-1	11.8	2.51	10	70	25
WASP-2	12.0	2.15	20	90	14
XO-1	11.7	3.94	20	40	10
HAT-P1	10.4	4.46	15	80	18

Table 1. Maximum timming accuracy achievable from a single transit observation. We have assumed that one photometric point per minute with $\epsilon_0 = 1$ mmag is obtained during for each object. The numbers of this table are orientative. Using (7), these results can be easily extrapolated to the particular observing circumstances imposed by a given instrument.

- The simultaneous measurement of a given transit by different instruments can help to reduce the uncertainities due to systematic errors in the photometric measurements.

4. Resources

A list of the known transiting exoplanets and low mass eclisping binaries with the predicted transit events and links to the Simbad entries for the stars is available in

`http://www.am.ub.es/~anglada/`
`http://www.am.ub.es/~anglada/tatooine/targets/exoplanets/exoplanet_list.html`

Update material, light curves, observations and bibliography related to the known exoplanets and their host stars is available through

`http://vo.obspm.fr/exoplanetes/encyclo/index.php`
`http://planetquest1.jpl.nasa.gov/atlas/atlas_index.cfm`

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