Testing the Rate of False Planetary Transits due to Binary Star Blending

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Abstract
We investigate the rate of false planetary transit detection due to blending with eclipsing binaries. Our approach is purely empirical and is based on the analysis of the artificially blended light curves of the eclipsing binary stars in the Large Magellanic Cloud from the archive of the Optical Gravitational Lensing Experiment (OGLE). Employing parameters that characterize the significance of the transit and the amplitude of the variation out of the transit, we can substantially limit the number of potential false positives. Further constraint comes from the expected length of the transit by a possible planetary companion. By the application of these criteria we are left only with 18 candidates from the full sample of 2495 stars. Visual inspection of these remaining variables eliminates all of them for obvious reasons (e.g., for visible fingerprints of orbital eccentricity). We draw the attention to the short-period stars, where the false alarm rate is especially low.

1. Introduction
It is well known that blended binaries are the most significant sources of confusion in searching for planetary transits (Brown 2003). Although the ultimate approach to this problem cannot avoid the tedious procedure of high-dispersion spectroscopic analysis (e.g., Mandushev et al. 2005; Bouchy et al. 2005), there have been additional simple methods suggested, based purely on the analyses of the light curves. Drake (2003) drew the attention to the gravitational and thermal effects of a stellar companion on the luminosity variation out of the eclipse (see also Sirko & Paczyński 2003). Seager & Mallén-Ornelas (2003) suggested a careful analysis of the transit shape. A similar approach was recommended by Tingley (2004). Recently, Tingley & Sackett (2005) studied the transit duration and depth as useful parameters in filtering out most of the stellar companion candidates.

The goal of the present work is to apply a set of conditions, similar to the ones mentioned above, on a homogeneous sample of observed binary stars with artificial blending added, and investigate if it is possible to filter them out as false positives from a list of transit candidates.

The data utilized in this work comes from the OGLE LMC binary database of Wyrzykowski et al. (2003). It contains 2681 objects, but only 2495 are used (the remaining 186 stars have less than 100 data points per star and often show high noise). There are EA, EB and EW stars in the sample.

2. Methodology and Tools
For the sake of simulating realistic blending scenario, we add constant intensity to each light curve and adjust it to get nearly the same total range of variation of 0.01 mag for all stars. In this way the signal-to-noise ratio remains the same as in the original data. The result can be extrapolated to higher noise level by proper scaling with the number of data points (see also Sect. 5).

The most important ingredients of our analysis are the following:

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• All blended light curves are searched for periodic transits by the BLS method (see Kovács et al. 2002). We note that the significance of the detection for all variables is very high.

• In order to characterize the statistical significance of the transit in the folded light curve derived from the preceding analysis, we introduce the Dip Significance Parameter (DSP) defined as follows:

$$DSP = \delta (\sigma^2/N_{tr} + A_{OOTV}^2)^{-\frac{1}{2}} ,$$

where $\delta$ is the depth of the transit, $\sigma$ is the standard deviation of the $N_{tr}$ in-transit data points, $A_{OOTV}$ is the peak amplitude in the Fourier spectrum of the Out of Transit Variation (OOTV, given by the folded time series with the exclusion of the transit).

• The significance of the main periodic signal in the OOTV is characterized by the Signal-to-Noise Ratio (SNR) of the Fourier spectrum of the OOTV (excluding the transit):

$$\text{SNR}_{OOTV} = \sigma_{A}^{-1}(A_{OOTV} - \langle A \rangle) ,$$

where $\langle A \rangle$ and $\sigma_{A}$, respectively, denote the average and the standard deviation of the Fourier spectrum.

• We would like to exclude stellar companions characterized by too long transit/eclipse durations. For this goal we compute the expected transit length (i.e., an upper limit of it) for a hypothetical planetary companion with G–M primaries. The following relations are used:

$$a = \left( \frac{GM^2}{4\pi^2} \right)^{\frac{1}{3}} , \quad \tan \alpha = \frac{R}{\sqrt{a^2 - R^2}} , \quad Q_{\text{tran}} \equiv T_{\text{transit}}/P = \frac{\alpha}{\pi} ,$$

with $a$, $R$, $M$, $P$, $G$ denoting the semi-major axis, stellar radius, stellar mass, orbital period and gravitational constant, respectively. The $R, M$ values correspond to Main Sequence stars as given in Lang (1992).

We add the following comments to the above definitions: Eq. (1) takes into consideration a possible OOTV, Eq. (2) yields significance limits on the OOTV. Although the two quantities are not completely independent, they are useful in characterizing different aspects of the morphology of the light curve. Eqs. (1) and (2) yield more general quantification of the OOTV than a simple few-component Fourier fitting, assuming tidal and/or reflection effects (Drake 2003; Sirko & Paczyński 2003). Eq. (3) assumes central transit, thereby giving an upper limit on the relative transit duration. More sophisticated treatment of the fractional transit length $Q_{\text{tran}}$ can be found in, e.g., Tingley & Sackett (2005). Theoretical OOTV amplitudes are given in Drake (2003). Methods on massive light curve analysis and binary model fitting have recently been published by Devor (2005).

3. Confidence levels

In order to estimate proper cutoff values for DSP and SNR_{OOTV} for selecting significant transit-like events, we generate artificial time series without a real signal, but with a Gaussian flux distribution on the time base of the observed data. For testing DSP, we use all data points, whereas for SNR_{OOTV} we exclude the observed time moments of transit as derived by the BLS routine on the original data. This test yields estimates on the low boundaries of the confidence levels, because the real data are correlated at various degrees due to the presence of the systematics inherent in the data reduction (see Kruszewski & Semeniuk 2003).

The distribution functions are shown in Fig. 1. Numerical values at the tails of the distributions are as follows: For DSP the $P < 0.01$ and $P < 0.001$ confidence limits are $DSP > 6.4$ and $DSP >$
The same limits for \( \text{SNR}_{\text{OOTV}} \) are \( \text{SNR} > 5.5 \) and \( \text{SNR} > 6.6 \). Obviously, feasible transit candidates are those events that show high DSP, but \( \text{SNR}_{\text{OOTV}} \) is low. The above values justify the use of our “soft” cutoffs (meaning that we do not even loose marginal candidates) of \( \text{DSP} > 6.0 \) and \( \text{SNR}_{\text{OOTV}} < 7.0 \) for transit selection in this sample.

**Fig. 1.** Probability distribution functions of the SNR of the OOTV and of the DSP of the transit for pure Gaussian test signals generated on the OGLE timebase. These diagrams yield significance levels for the above parameters when employed on observed data.

4. Results

4.1 Distribution of the OOTV peak frequencies

Fig. 2 shows that most of the peak frequencies of the Fourier spectra of the OOTVs are grouped around integer frequencies (in the units of the orbital frequency), indicating that tidal and/or reflection effects are the dominating factors in causing OOTV. Some 75% of the stars exhibit OOTV with peak frequencies \( n \pm 0.2 \).

**Fig. 2.** Empirical probability density function of the observed OOTV peak frequency \( \nu_{\text{OOTV}} \) (in the units of the orbital, i.e. BLS peak frequency).

4.2 Orbital frequency vs. \( Q_{\text{tran}} \)

The left panel in Fig. 3 shows the \( Q_{\text{tran}} \) values derived for the full sample of 2495 stars without applying any parameter cuts. The right panel shows the result after the application of the DSP and \( \text{SNR}_{\text{OOTV}} \) cutoffs. There remain only 18 stars satisfying both of these cuts and the \( Q_{\text{tran}} < 1.1Q_{\text{tran,G0V}} \) constraint, where \( Q_{\text{tran,G0V}} \) is the estimated fractional transit time with a G0V primary. (The factor 1.1 is used for rough error allowance in the \( Q_{\text{tran}} \) values).
4.3 The ‘transit candidates’

The folded light curves of the 18 binaries that passed the basic steps of transit selection are shown in Fig. 4. Except for the following 3 stars, all exhibit obvious signs of stellar binary components (more or less well-defined secondary eclipse, uneven distribution of the eclipses due to eccentric orbit). Closer inspection of the remaining 3 stars shows the following:

- **052730.57-695**: The secondary eclipse preceding the primary is only marginally visible (it is somewhat more easily identified in the 1P-folded light curve).

- **051734.54-692**: Observed in fields #7 and 8 (field #8 data are shown). The light curve from field #7 contains more data and yields four times longer period than the one in field #8. The 4P-folded light curve shows two clear eclipses of different depth.

- **051108.69-691**: Period is almost exactly 8 days. Folding with P/2 definitely shows eccentricity, as the two minima are offset from each other in phase.

5. Conclusions

- Detailed light curve analysis combined with constraints posed by theoretical transit lengths shows that in a hypothetical blending scenario NONE of the 2495 binaries in the OGLE LMC database could be false positive planetary candidates.

- Chance of confusion due to blending is especially low among short-period \((P < 1.5 \text{ d})\) binaries.

- Since for the same signal the signal-to-noise ratio scales with the square of the standard deviation \((\sigma)\) of the noise and the present OGLE sample has fairly low \(\sigma\), in current wide field surveys one needs to gather a large number of data points per star in order to reach the above level of confidence in selecting false positives.

- This test indicates that careful analysis of the light curves (if data quality permits) indeed leads to the elimination of large number of binary blends, thereby narrowing down the list of potential planetary candidates.
Fig. 4. Folded light curves of the 18 variables satisfying transit selection conditions on DSP, SNROOTV and $Q_{\text{tran}}$ (see text for details). 

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