Search for Planetary Candidates within the OGLE Stars

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ABSTRACT

We propose a method to distinguish between planetary and stellar companions to stars which present a periodic decrease in brightness, interpreted as a transit. Light curves from a total of 177 stars from the OGLE project were fitted by the model which simulates planetary transits using an opaque disk in front of an image of the Sun. The simulation results yield the orbital radius in units of stellar radii, the orbital inclination angle, and the ratio of the planet to the star radii. Combining Kepler’s third law with a mass-radius relation for main sequence stars, it was possible to estimate values for the masses and radii of both the primary and secondary objects. This model was successfully tested with the confirmed planets orbiting the stars HD 209458, TrES-1, OGLE-TR-10, 56, 111, 113, and 132. The method consists of selecting as planetary candidates only those objects with primary densities between 0.7 and 2.3 solar densities (F, G, and K stars) and secondaries with radius less than 1.5 Jupiter radius. The method is not able to distinguish between a planet and a dwarf star with mass less than 0.1 \(M_\odot\), such as OGLE-TR-122. We propose a selection of 28 planetary candidates (OGLE-TR-49, 51, 55, 63, 71, 76, 90, 97, 100, 109, 114, 127, 130, 131, 134, 138, 140, 146, 151, 155, 159, 164, 165, 169, 170, 171, 172, and 174) for high resolution spectroscopy follow up.

Subject headings: planetary systems; eclipses

1. Introduction

Since the discovery of the first extra-solar planet orbiting a solar-like star (Mayor & Queloz 1995), there has been an increased interest in the search for planets around other stars. Presently, over 150 planets have already been discovered (see The Extra-Solar

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Planets Encyclopedia at www.obspm.fr/encycl/encycl.html). The only way to decide if a companion object is a planet or a dim star is through the measurement of its mass.

There are basically two methods for planet detection commonly applied, both of which are heavily biased toward giant planets in close in orbits. The most used method is radial velocity measurements of the star motion around the center-of-mass of the planet-star system. This method, however, yields only the mass lower limit, $M_p \sin(i)$, where $M_p$ is the secondary mass and $i$ is the inclination angle of the orbit. Another way to detect planets is through the observation of eclipses caused by planetary transits in front of the parent star. Because of the limited precision attained with ground based observations, only objects with sizes of the order or larger than Jupiter, which cause $\sim 1 - 2\%$ dips in the light curve, can be detected. Due to their similar sizes, however, the transiting objects could be extra-solar planets, brown dwarfs, or M-type dwarfs. Moreover, shallow transits due to blending may also be mistaken as planetary eclipses. Both methods are complementary, in the sense that it is possible to fully characterize the companion by its mass and radius, plus the orbital parameters (semi major axis, inclination angle, and period).

Until 2002, the transit of only one planet, HD 209458b, had been observed (Charbonneau et al. 2000; Henry et al. 2000). This scenario changed when the Optical Gravitational Lensing Experiment (OGLE) found evidences of transits in the light-curves of 177 stars (Udalski et al. 2002a,c,b, 2003, 2004). The presence of a planet was confirmed on five of those stars by follow up of radial velocity measurements: OGLE-TR-10 (also suggested by Dreizler et al. 2002), OGLE-TR-56 (Konacki et al. 2003a,b; Torres et al. 2004), OGLE-TR-111 (Pont et al. 2004), OGLE-TR-113 (Konacki et al. 2004; Bouchy et al. 2004) and OGLE-TR-132 (Bouchy et al. 2004). The TrES multisite transiting planet survey also yields the detection of a transiting Jupiter-sized planet (Alonso et al. 2004).

Previous authors have also investigated the nature of the OGLE star companions to identify stellar binaries. The methods used varied from the detection of ellipsoidal variation (Drake 2003; Sirko & Paczyński 2003), to spectroscopic surveys (Torres et al. 2004; Konacki et al. 2003b; Dreizler et al. 2002), and infrared spectroscopy (Gallardo et al. 2005). Drake (2003) searched for sinusoidal modulations in the light curves due to the ellipsoidal form of the stellar envelope caused by the proximity of a second star. Extending the analysis of Drake (2003), Sirko & Paczyński (2003) found ellipsoidal variations above the 3 sigma level in 30 of the studied stars, indicating the presence of a red dwarf companion. Tingley & Sackett (2005) have also devised a method which employs an exoplanet diagnostic $\eta$ in order to identify the best planetary candidates from a transit search.

Here we propose a test for distinguishing between planetary and stellar companions based on transit observations, and apply this method to the stars observed by the OGLE
survey. The next section describes the transit simulation using an image of the Sun. Section 3 presents the result of the best fit to the OGLE data along with the discussion. Finally, the conclusions are presented in the last section.

2. The method: “planetary” transit across the Sun

A white-light image of the Sun from Big Bear Solar Observatory is used to simulate the parent star (as in Silva 2003). The advantage of using an image of the Sun is that limb darkening is already taken into account. It is true that some stars have quadratic limb darkening (e.g. HD 209458, Brown et al. 2001) instead of the linear limb darkening, as in the solar case, however, due to the large uncertainty of the OGLE data it is not possible to distinguish between these two.

The secondary object is represented by an opaque disk of radius \( R_p/R_s \), where \( R_p \) is the “planet” radius whereas \( R_s \) is the radius of the primary star. The position of the “planet” in its orbit is calculated for each time interval according to the orbital parameters: inclination angle, \( i \), and semi-major axis, \( a/R_s \) (in units of the stellar radius). All simulations were performed assuming the orbit to be circular, that is null eccentricity. This assumption is probably valid due to the strong gravitational tidal forces and the close proximity to the primary star. The orbital periods used were those given by the OGLE project.

Figure 1 shows the effect of varying the three parameters used in the transit simulation, namely, \( R_p/R_s \), \( a/R_s \), and \( i \). The effect of increasing the secondary radius, \( R_p/R_s \), is to strengthen the dimming in the light curve (Figure 1a). By decreasing the distance of the secondary to its parent star, \( a/R_s \), the phase interval of the transit is increased (Figure 1b). The latitude of the transit is determined by the orbit inclination angle and the orbital radius, which in turn changes both the phase interval of the transit and its depth (Figure 1c).

The light curve of a particular star containing a dimming, interpreted as a transit from a secondary faint object, is then fit by the simulation. The parameters of the transit are chosen from the best fit to the data, that is, minimum \( \chi^2 \).

In order to test the method, observations of known planets such as HD209458b (Deeg et al. 2001) and TrES-1 (Alonso et al. 2004) were used. The best transit fit to the data (crosses) is shown as a solid line in Figure 2, and the parameters obtained are given in Table 1. The same method was applied to the stars observed by the OGLE project which, through radial velocity measurements, had their planetary companions verified, that is, OGLE-TR-10, 56, 111, 113, and 132. For each object, the first line of the table
shows the parameters obtained from the observations, as listed in The Extra-Solar Planets Encyclopedia. The parameters obtained from the best fit, listed on Table 1 (second line for each object, denominated “model”), agree with the published values within the uncertainty estimates. In order to estimate the uncertainty of the model parameters \( R_p/R_s \), \( a/R_s \), and \( i \), a 1000 light curves were generated by varying randomly each of the 3 parameters within reasonable intervals. From these, we selected only those light curves which values remained within the envelope defined by \( \pm 1\sigma \) of the observed light curve. This standard deviation was calculated from the data outside the transit. Finally, the uncertainty was estimated from the distribution of the parameter values of these selected light curves.

For a second test to the model, we used the data from OGLE-TR-122, which has been identified as binary system (Pont et al. 2005) with masses \( M_1 = 0.98M_\odot \) and \( M_2 = 0.092M_\odot \), the latter low mass star has a radius of only \( R_2 = 0.12R_\odot \). The results from our model (also shown in Figure 2 and listed on Table 1) are \( M_1 = 0.81M_\odot \), \( M_2 = 0.05M_\odot \), and \( R_2 = 0.94R_\odot \), agreeing quite well with the observations. Yet another test performed was to fit the model to a synthetic light curve which was generated for a binary system with a primary star of \( 4M_\odot \) and a secondary of \( 0.32M_\odot \) with radius \( R_2 = 3.92R_J \), on an orbit of \( i = 84^\circ \) and semi-diameter of 0.075 A.U.. After adding random noise to the light curve (shown in Figure 2), the model yields \( M_1 = 3.75M_\odot \), \( M_2 = 0.29M_\odot \), \( R_2 = 3.62R_J \), \( i = 85.3^\circ \), and orbital radius of 0.074 A.U.. As can be seen, once more the model seems to reproduce well the expected values.

### 3. Planetary versus stellar companion

From a total of 177 stars detected by the OGLE project (Udalski et al. 2002a,c,b, 2003) whose light curve presented periodic dimming, four were discarded for not having their period listed (OGLE-TR-43 to 46). A remainder of 173 stars were analyzed, and the secondary object and its orbital parameters obtained by minimizing the difference between the data and the transit simulation, as described in the previous section. The parameters, \( R_p/R_s \), \( a/R_s \), and \( i \), obtained from the model best fit to the data are plotted as histograms in Figure 3, for the 173 stars studied.

The radius of the secondary object, \( R_p/R_s \), in units of the primary radius, are plotted in the top left panel of Figure 3. The dashed vertical line in this panel represents the relative size of Jupiter with respect to the Sun, and indicates that the majority of companions are larger than the relative size of Jupiter. The orbital distance, \( a/R_s \) determined from the model assuming circular orbits were found to be between 2-20 stellar radii, and are shown in the top right panel of Figure 3. Most orbital inclination angles are close to 90\(^\circ\), which
is expected for the detection of transits. Angles smaller than 80° may be an indication of grazing eclipses and their respective results should not be considered. The bottom right panel of the figure shows the density of the primary star inferred from the observations, estimated by the following relationship obtained using Kepler’s third law:

\[
\rho = \frac{M_1 + M_2}{R_1^3} = \frac{4\pi^2}{GP^2} \left( \frac{a}{R_s} \right)^3
\]

where \(P\) is the period and \(a/R_s\) is the orbital radius, both quantities directly inferred from the fit without any further assumptions. If \(M_2 \ll M_1\) then \(\rho\) is the density of the primary star, when this is not true, however, this density will be overestimated. Only those stars with densities with values within the dotted lines, corresponding to F, G, and K stars, will be further considered, as discussed in the next section.

The aim of this work is to propose a method for selecting the best planetary candidates for a follow up with radial velocities measurements, which is very expensive due to the time requirement on large telescopes with high precision spectrographs. Below we explain how it is possible to infer the absolute values of the mass and radius of both the primary and secondary objects, and therefore determine the companion object radius and its orbital distance in absolute values.

In order to calculate the four unknowns \(M_1\) (or \(M_s\)), \(R_1\) (or \(R_s\)), \(M_2\), and \(R_2\), the masses and radii of the primary and secondary objects respectively, we need four equations. The first one is Kepler’s third law:

\[
\left( \frac{a}{R_s} \right)^3 = \frac{GP^2}{4\pi^2 R_1^3} (M_1 + M_2),
\]

where \(a/R_s\) is obtained from the best fit to the data. The second equation is given by the ratio of the primary and secondary radii: \(R_p/R_s = R_2/R_1\), where the left handside is determined from the depth of the transit in the observed lightcurve. The two last equations are obtained by applying a mass-radius relationship for main sequence stars, \(R_s/R_\odot = (M_s/M_\odot)^{0.8}\) (Cox 2000), for both the primary and the secondary object. Thus one can determine the mass and radius of both objects from the four equations listed above. Here we have considered both objects to be main sequence stars. Note that for a companion with a tenth of a solar mass, this mass-radius relationship yields a radius of about 1.5 times that of Jupiter, making it impossible to distinguish between a planet and a dwarf star based only on transit data.

Using the above equations, we calculate the value of the primary radius in units of
solar radius, and thus determine the absolute value of the orbital semi-diameter in A.U.. Histograms of these parameters are plotted in Figure 4. Primary stellar masses in units of solar mass (plotted on the top left panel of Figure 4) vary between 0.5 and 7 $M_{\odot}$, with a maximum value around one solar mass. The top right panel of the figure displays the mass of the secondary object, which is not the real value if this is a planet. The radius of the secondaries, ranging from 0.5 to 8 Jupiter’s radius, is shown in the bottom left panel. The most common companion radius being about 1.5 $R_J$. The semi-diameter of a circular orbit is shown in the bottom right panel, with values in the range between 0.01 and 0.15 A.U., peaking at 0.05 A.U..

As mentioned above, in the case that the secondary object is a planet, then the value of $M_2$ will not be real, however, its radius $R_2$ will be a good estimate of the true value. If $M_1 >> M_2$ then the mass of the primary star is given by

$$\frac{M_s}{M_{\odot}} = \left( \frac{G P^2 M_\odot}{4\pi^2 R_\odot^3 (a/R_s)^2} \right)^{1/1.4}$$

and its radius is obtained from the mass-radius relationship given above. A similar analytical model has been proposed by Seager & Mallén-Ornelas (2003), using the same stellar mass-radius relation, however, in their model the authors do not consider the stellar limb darkening. In the case where the mass of the secondary, $M_2$, is much less than that of the primary, $M_1$, then in the above equation $M_s = M_1$. When the secondary is a dwarf star, however, $M_s = (M_1^{2.4}/(M_1 + M_2))^{1/1.4}$, and the resulting $M_s$ will be less than $M_1$. Hence equation 2 should not be used to estimate the mass of the primary star.

To rule out stellar companions, first we need to eliminate large stars such as A, B, and O stars with radius at least 10 times larger than a 0.3-0.5 $M_{\odot}$ secondary star that can cause a transit of 1-2% dimming. For this we use the density of the primary star. Since, here we are interested in only F, G, and K stars so that the secondary companion will have radii of the order of Jupiter, we will consider further only those stars with densities between 0.7 and 2.3 that of the Sun. The lower limit excludes big stars such as A, B, or O stars, whereas the upper density limit was chosen as that of the densest star known to harbor planets (see Table 1). Results of densities larger than about 2 either represent M dwarf stars or maybe binary systems. By adopting this criterion, only 72 candidates remained (including the 5 stars already known to harbor planets listed in Table 1), yielding a total of 42% of the OGLE stars.

In order to better constrain the planetary candidates, our initial list of 67 OGLE stars (the 5 bonafide planets were excluded) were checked against the stellar companions
confirmed by the previous work cited in the Introduction. From these a total of 11 stars were either listed as showing ellipsoidal variation or are giants, implying that their companion is not an exoplanet.

Therefore, a more conservative criterion was established in order to improve our method: besides the constraint on the density of the primary star, for the secondary to be considered a planet candidate its radius has to be less than 1.5 \( R_J \). Note that due to the adopted mass-radius relationship, this criterion is equivalent to considering only those secondaries with masses less than 0.1 \( M_\odot \). This shortened the candidate list to the 28 stars displayed in Table 2, plus OGLE-TR-122. The uncertainties were estimated in the same way as described previously. The parameters of these selected stars are shown as the gray histograms in Figure 4.

These 28 objects were confronted with the results of Tingley & Sackett (2005), where a secondary is considered a planet candidate if the parameter \( \eta_p < 1 \). Only 6 stars (OGLE-49, 151, 159, 165, 169, and 170) failed the comparison having \( \eta \) larger than unity. From high resolution spectroscopy, Pont et al. (2005) showed that OGLE-TR-122 is a very low mass star (0.092 \( M_\odot \)), with about the same size as Jupiter. Since its mass is less than one tenth that of the primary, this stellar companion could not have been detect by our method. Nevertheless the detection of such low mass stars are interesting and such objects deserve further study.

4. Conclusions

A method for selecting the best planetary candidates has been presented here and applied to 173 stars with evidence of low luminosity companion transits observed by the OGLE project. The method consists of simulating a transit by an opaque disk, the “planet”, in front of a white light image of the Sun, representing the star. Besides the orbital period which is directly obtained from the OGLE data, three parameters are determined from a best fit of the model to the data: (i) ratio of companion to star radii, \( R_p/R_s \); (ii) orbital semi-diameter (assuming circular orbit) in units of stellar radius, \( a/R_s \); and (iii) orbit inclination angle, \( i \).

In order to obtain absolute values for the secondary radius and its orbital distance, it is necessary to determine the primary radius. Combining Kepler’s 3rd law with a mass-radius relationship for main sequence stars (\( R_s \propto M_s^{0.8} \)) and the observed transit depth, it was possible to infer the mass and radius of the primary and secondary objects. This method worked quite well for the 7 known planetary companions: HD209458b, TrES-1,
OGLE-TR-10, 56, 111, 113, and 132, as can be seen from Table 1.

At first only stars with densities between 0.7 and 2.3 solar density (corresponding to F, G, and K stars) were considered. Excluding the 5 known planets, a total of 67 stars resulted. When comparing these stars with those studied by previous authors, we noted that this was not a sufficient criterion for ruling out stellar companions. Hence, a further constraint on the radius of the secondary was adopted: only those companions with radius < 1.5\(R_J\) were considered, similar to Dreizler et al. (2002). We point out that this method is not able to distinguish between true planets and dwarf stars with masses of the order or less than 0.1 \(M_\odot\), since their sizes are similar to that of Jupiter (e.g. OGLE-TR-122). Nevertheless, the study of these low mass stars is also interesting.

These criteria resulted in 28 planet candidates, listed in Table 2, comprising less than 16% of the OGLE stars. We propose that these stars should have high precision spectroscopic follow up in order to confirm or not, by the estimate of their mass, if they truly are planets.

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Table 1: Best fits from the model

| Star           | $M_s (M_\odot)$ | $R_p (R_J)$ | $a$ (A.U.) | $i$ (°)     |
|----------------|----------------|-------------|------------|------------|
| HD209458 obs. | 1.05           | 1.32±0.05   | 0.045      | 86.1±0.1   |
| model         | 1.14±0.22      | 1.35±0.20   | 0.047±0.003| 87.2±0.6   |
| TrES-1 obs.   | 0.87±0.03      | 1.08±0.18   | 0.0393±0.0007| 88.2±1.0   |
| model         | 0.86±0.21      | 1.14±0.25   | 0.0390±0.0028| 88.4±1.2   |
| OGLE-TR-10 obs. | 1.22±0.04     | 1.24±0.09   | 0.0416±0.007| 89.2±2.0   |
| model         | 1.09±0.20      | 1.32±0.18   | 0.0428±0.0026| 88.1±0.6   |
| OGLE-TR-56 obs. | 1.04±0.05     | 1.23±0.16   | 0.0225±0.0004| 81.0±2.2   |
| model         | 0.80±0.23      | 0.86±0.19   | 0.0206±0.0020 | 85.4±0.6   |
| OGLE-TR-111 obs. | 0.82±0.15    | 1.00±0.13   | 0.047±0.001 | 86.5-90    |
| model         | 0.96±0.21      | 1.16±0.19   | 0.049±0.003 | 88.1±0.6   |
| OGLE-TR-113 obs. | 0.77±0.06     | 1.08±0.07   | 0.0228±0.0006| 90.0±0.3   |
| model         | 0.72±0.18      | 1.09±0.21   | 0.0223±0.0019 | 90.0±0.3   |
| OGLE-TR-132 obs. | 1.35±0.06     | 1.13±0.08   | 0.0306±0.0008| 85±1       |
| model         | 1.2±0.3        | 0.90±0.17   | 0.0292±0.0025| 90.0±0.3   |
| OGLE-TR-122 obs. | 0.98±0.14     | 1.17±0.16   |            | 88-90      |
| model         | 0.81±0.07      | 0.96±0.08   | 0.0672±0.0021 | 89.3±0.5   |

The observational parameters are taken from The Extra-solar Planets Encyclopedia (www.obspm.fr/encycl/encycl.html).

Pont et al. (2005)
Table 2: Planetary candidates

| OGLE-TR | $M_s (M_\odot)$ | $R_p (R_J)$ | $a$ (A.U.) | $i$ (°) |
|---------|----------------|-------------|------------|---------|
| 49      | 0.99±0.20      | 1.43±0.24   | 0.0377±0.0027 | 89.9 ±0.3 |
| 51      | 0.79±0.13      | 1.22±0.16   | 0.0263±0.0014 | 89.9 ±0.3 |
| 55      | 1.30±0.34      | 1.36±0.28   | 0.0462±0.0039 | 85.9 ±0.6 |
| 63      | 1.21±0.35      | 1.07±0.24   | 0.0217±0.0022 | 87.6 ±0.6 |
| 71      | 0.87±0.13      | 1.28±0.17   | 0.0485±0.0024 | 87.1 ±0.5 |
| 76      | 1.06±0.24      | 1.28±0.22   | 0.0330±0.0024 | 86.9 ±0.6 |
| 90      | 0.84±0.19      | 1.19±0.21   | 0.0189±0.0014 | 82.3 ±0.6 |
| 97      | 1.44±0.42      | 1.43±0.33   | 0.0151±0.0016 | 79.5 ±0.6 |
| 100     | 0.99±0.35      | 1.21±0.33   | 0.0172±0.0019 | 89.6 ±0.4 |
| 109     | 1.62±0.31      | 1.18±0.16   | 0.0161±0.0011 | 89.0 ±0.6 |
| 114     | 0.90±0.14      | 1.16±0.14   | 0.0270±0.0014 | 87.8 ±0.6 |
| 127     | 0.83±0.23      | 0.85±0.18   | 0.0285±0.0026 | 84.3 ±0.6 |
| 130     | 0.76±0.15      | 1.33±0.21   | 0.0509±0.0032 | 86.5 ±0.4 |
| 131     | 0.82±0.31      | 0.75±0.22   | 0.0278±0.0032 | 85.4 ±0.6 |
| 134     | 1.31±0.16      | 1.17±0.11   | 0.0587±0.0025 | 88.3 ±0.6 |
| 138     | 0.77±0.23      | 0.71±0.15   | 0.0343±0.0031 | 87.7 ±1.0 |
| 140     | 0.85±0.25      | 1.06±0.27   | 0.0418±0.0041 | 87.0 ±1.2 |
| 146     | 0.80±0.15      | 0.94±0.14   | 0.0373±0.0024 | 88.2 ±1.1 |
| 151     | 0.97±0.36      | 1.02±0.25   | 0.0252±0.0027 | 89.2 ±0.8 |
| 155     | 1.20±0.38      | 0.95±0.23   | 0.0630±0.0059 | 87.8 ±1.1 |
| 159     | 1.16±0.25      | 1.24±0.19   | 0.0339±0.0024 | 88.5 ±1.0 |
| 164     | 1.40±0.36      | 1.09±0.22   | 0.0422±0.0038 | 87.1 ±1.2 |
| 165     | 1.07±0.28      | 1.02±0.20   | 0.0405±0.0035 | 87.6 ±1.1 |
| 169     | 1.16±0.44      | 0.80±0.22   | 0.0405±0.0047 | 88.6 ±1.0 |
| 170     | 1.43±0.33      | 1.07±0.17   | 0.0567±0.0042 | 88.8 ±0.9 |
| 171     | 0.74±0.26      | 0.61±0.14   | 0.0290±0.0031 | 87.8 ±1.2 |
| 172     | 1.24±0.61      | 0.86±0.31   | 0.0310±0.0050 | 88.5 ±1.1 |
| 174     | 0.81±0.21      | 0.58±0.13   | 0.0389±0.0038 | 87.5 ±1.1 |
Fig. 1.— Influence of varying the parameters of the simulation: a) secondary radius, $R_p/R_s$; b) orbital radius, $a/R_s$; and c) inclination angle, $i$.

Fig. 2.— Best fit for the transit model (solid line) for stars HD209458, TrES-1, OGLE-TR-10, 56, 111, 113, 132, and 122. The parameters obtained are listed on Table 1. The crosses represent the data. Also shown in the top right panel is the modeled binary system used as a test to the method.

Fig. 3.— Histograms of the parameters obtained from the best fit to the transit data: secondary radius, $R_p/R_s$, orbital radius $a/R_s$, inclination angle $i$, and primary star density (in units of solar density) for the 173 OGLE stars.

Fig. 4.— Histograms of the secondary parameters after using the mass-radius relationship for main sequence stars: primary and secondary masses in units of solar mass, secondary radius, $R_p$ in units of Jupiter’s radius, and orbital semi-diameter $a$ in A.U. for the 173 OGLE stars. The shaded histograms correspond to the selected stars (including those known to harbor planets) which have densities between 0.7 and 2.3 solar density and secondary objects smaller than 1.5 Jupiter radius.
