DETECTION OF KOI-13.01 USING THE PHOTOMETRIC ORBIT

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ABSTRACT

We use the KOI-13 transiting star–planet system as a test case for the recently developed BEER algorithm, aimed at identifying non-transiting low-mass companions by detecting the photometric variability induced by the companion along its orbit. Such photometric variability is generated by three mechanisms: the beaming effect, tidal ellipsoidal distortion, and reflection/heating. We use data from three Kepler quarters, from the first year of the mission, while ignoring measurements within the transit and occultation, and show that the planet’s ephemeris is clearly detected. We fit for the amplitude of each of the three effects and use the beaming effect amplitude to estimate the planet’s minimum mass, which results in \( M_p \sin i = 9.2 \pm 1.1 M_J \) (assuming the host star parameters derived by Szabo et al.). Our results show that non-transiting star–planet systems similar to KOI-13.01 can be detected in Kepler data, including a measurement of the orbital ephemeris and the planet’s minimum mass. Moreover, we derive a realistic estimate of the amplitudes uncertainties, and use it to show that data obtained during the entire lifetime of the Kepler mission of 3.5 years will allow detecting non-transiting close-in low-mass companions orbiting bright stars, down to the few Jupiter mass level. Data from the Kepler Extended Mission, if funded by NASA, will further improve the detection capabilities.

Key words: methods: data analysis – planets and satellites: detection – stars: individual (KOI-13)

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1. INTRODUCTION

Traditionally, before the age of continuous high-precision space-based photometry, the investigation of low-mass transiting companions used spectroscopy primarily to study the system’s orbit via the spectroscopic Doppler effect, and photometry primarily to study the system’s geometric characteristics through measurements of eclipse (transit and occultation) light curve. However, it has been shown that space-based photometry from missions such as Kepler (Borucki et al. 2010; Koch et al. 2010) and CoRoT (Rouan et al. 1998; Aurière et al. 2009) can be used to detect optical variability induced by a low-mass companion along its orbital motion, down to the planetary mass level (e.g., Jenkins & Doyle 2003; Mazeh & Faigler 2010; Welsh et al. 2010). Hereafter, we refer to the measurement of photometric variability correlated with the orbit as orbital photometry.

Recently it was shown by Faigler & Mazeh (2011) that analysis of orbital photometry can be used for detecting new non-eclipsing binary systems, where the secondary (star or planet) can be of low-mass, down to the planet mass range. Their BEER algorithm is aimed at identifying the system’s ephemeris and estimating the secondary minimum mass, \( M_2 \sin i \), where \( M_2 \) is the mass of the secondary and \( i \) the angle between the orbital angular momentum axis and the line of sight. In addition, Faigler & Mazeh (2011) presented the detection of two targets showing an orbital photometry signal, which in both cases suggests the presence of a non-eclipsing companion whose minimum mass is close to 70 \( M_J \). We use here the same method, with some modifications and additions, and apply it to the recently discovered transiting planet system KOI-13.01 (Rowe et al. 2011; J. Rowe et al. 2011, in preparation), containing a massive planet orbiting a bright A-type host star (\( K_p = 9.96 \text{ mag}; \) KIC ID 9941662) every 1.76 days. Since that system is transiting, we use it as a test case for the approach of Faigler & Mazeh (2011). We use only the out-of-eclipse light curve to show whether non-transiting star–planet systems similar to KOI-13.01 can be discovered in Kepler data.

We briefly describe the various mechanisms inducing photometric variability along the orbit in Section 2. In Section 3 we present our data analysis and show that the out-of-eclipse data can be used to clearly detect the ephemeris of KOI-13.01. In our discussion in Section 4 we give an estimate of the companion minimum mass (which in this case is close to the true mass), and show that data from the entire 3.5 year Kepler mission lifetime are expected to allow detection of non-transiting close-in star–planet systems down to the Jupiter mass level. Our work is summarized in Section 5.

2. ORBITAL PHOTOMETRY

As described by Faigler & Mazeh (2011) photometric variability along the orbit can be induced by three mechanisms: (1) beaming (aka Doppler boosting), (2) tidal ellipsoidal distortion, and (3) reflection of light from the star by the planet. The third mechanism includes the effect of heating of the planetary atmosphere by the star’s radiation.

The tidal ellipsoidal and reflection effects are well known from observations of eclipsing binaries, while the beaming effect was observed only recently. The latter was described in Shakura & Postnov (1987), Loeb & Gaudi (2003), and Zucker et al.
A low-mass companion relative to the primary, and assumptions are a circular orbit, negligible luminosity for the host star’s radial velocity (RV) modulation semi amplitude, and orbit inclination angle, and semimajor axis, respectively, \( M_{s} \) and \( R_{s} \) are the host star’s (i.e., the primary star’s) mass and radius, respectively, \( M_{2} \) and \( R_{2} \) are the secondary mass and radius, respectively, \( P_{\text{orb}} \), \( i \), and \( a \) are the orbital period, inclination angle, and semimajor axis, respectively, \( K_{\text{RV}} \) is the host star’s radial velocity (RV) modulation semi amplitude, and \( c \) is the speed of light. The three coefficients \( \alpha_{\text{beam}} \), \( \alpha_{\text{ellip}} \), and \( \alpha_{\text{refl}} \) are each of order unity—see Faigler & Mazeh (2011) for more details.

The expressions above are approximations, where the primary assumptions are a circular orbit, negligible luminosity for the low-mass companion relative to the primary, and \( M_{2} \ll M_{s} \).

Using the above three equations we show in Figure 1 the expected amplitudes of the three effects for a star–planet system similar to KOI-13.01, and a range of orbital periods. The KOI-13.01 orbital period is marked by a vertical dashed line, where the expected amplitudes are an order of \( 10^{-3} \) to \( 10^{-6} \) in relative flux. We note that Figure 1 is plotted while assuming the light from the target is not blended on Kepler CCDs with light coming from nearby stars; such contamination will dilute the observed amplitudes.

3. DATA ANALYSIS AND RESULTS

We used here data from three Kepler quarters, Q2, Q3, and Q5. Data from Q1 and Q4 were avoided as they were produced using insufficient aperture size to collect all the flux of this saturated star, and data from Q0 (and Q1) show increased noise level relative to other quarters. We verified that using all data through Q5 gave identical results, albeit with larger error bars by a factor of \( \sim 2 \).

Before applying our analysis we applied two preprocessing steps. First, we ignored the in-eclipse points from all transits and occultations, removing 18.3% of the data.

The raw Kepler data include instrumental trends, temporal gaps, and discontinuities (or “jumps”) in the flux level. Correcting for these effects is important for detecting variability along the entire orbital phase, as opposed to the detection of eclipses the typical durations of which are only a small fraction of the entire orbit. For that end we applied a second preprocessing step where we divided the Kepler light curve into several continuous sections without gaps or jumps. The typical duration of each such section is 1–2 months. We fitted each section with a fifth degree polynomial and divided by the fit to get the corrected light curve, in relative flux. The fitting was done iteratively while ignoring \( 5\sigma \) outliers relative to the fit until no outliers were found. We checked that using a polynomial degree of 4 and 6 gave consistent results, within 0.5\( \sigma \). This step removed an additional 5.6% of the original three quarters data set, most of which from the start and end of the continuous sections.

The corrected light curve is shown in Figure 2 (top panel). Data from Q0, Q1 and Q4, that were not used in our analysis, are shown in gray. As can be seen in the figure the data from Q0 and Q1 containing the first 45 days of data have a larger scatter than the rest. The data we use in the following analysis, from Q2, Q3, and Q5, are shown in black. They contain 9689 Long Cadence measurements, each with an effective exposure time of 29.4 minutes, spanning 368.4 days. Figure 2 (bottom panel) shows a zoomed-in view of 10 days of data from Q5, where the orbital photometric variability can be visually identified.

To look for the orbital photometric signal, including the identification of the orbital period and phase, and the measurement of the amplitudes of each of the photometric effects, we followed the two-step BEER algorithm presented by Faigler & Mazeh (2011).

Step 1. The goal of the first step is to detect the orbital period. To do so we constructed a periodogram where for each trial period we fitted, in a linear least-squares manner, a double harmonic model (e.g., Shporer & Mazeh 2006; Shporer et al. 2010) including five parameters, or coefficients:

\[
f(t) = a_0 + a_1 \cos \left( \frac{2\pi}{P} t' \right) + a_1 \sin \left( \frac{2\pi}{P} t' \right) + a_2 \cos \left( \frac{2\pi}{P/2} t' \right) + a_3 \sin \left( \frac{2\pi}{P/2} t' \right),
\]  

(4)
Table 1

| Parameter                  | This Work                  | Borucki et al. (2011) |
|----------------------------|----------------------------|-----------------------|
| Orbital period, \( P_{\text{orb}} \) (days) | 1.7637 ± 0.0013            | 1.7635892 ± 0.000014  |
| Inferior conjunction time, \( T_0 \) (BJD) | 2455138.7439 ± 0.0013      | 2454953.56498 ± 0.00012 |

Figure 2. Top: KOI-13 *Kepler* Long Cadence light curve, after applying the steps described in Section 3, including removing the transit and occultation data. The data from Q0, Q1, and Q4 are shown in gray and were not used here. The data from Q2, Q3, and Q5 are shown in black. Bottom: zoomed-in view of a 10 day light curve during Q5 (without in-eclipse measurements).

Figure 3. The double harmonic periodogram (blue), where the strongest peak corresponds to the orbital period of 1.76 days. The solid vertical lines (black) at the top of the figure mark frequencies which are a sub harmonic or harmonics of the strongest peak. The dashed vertical lines (black) mark unidentified frequencies where one is a harmonic of the other. See the text for more details. (A color version of this figure is available in the online journal.)
We tried to estimate realistic errors on the fitted coefficients. The linear least-squares method provides us “formal” errors, but they do not account for possible remaining systematic trends in the Kepler light curve. To account for systematic trends we repeated our analysis while applying cyclic permutations to the residuals of our best-fit model (e.g., Carter & Winn 2009). Each of those permutations was generated by repeatedly shifting the residuals of every measurement and adding it to the model value of the subsequent point in the time series. The residual of the last measurement is added to the first point. Cyclic permutations keep the order of the residuals unchanged, preserving possible systematic trends, unlike random permutations. After analyzing all possible $10^4$ cyclic permutations, we examined the distributions of the resulting coefficients and took half the difference between the 84.13 and 15.87 percentiles to be the 1σ uncertainty. The coefficient’s distributions were highly symmetric about the median, and the latter were indistinguishable from the original fitted values. The errors derived this way were close to twice as large as the errors obtained directly from the linear least-squares method.

Our phase folded light curve based on the ephemeris derived here is presented in the top panel of Figure 4. That figure does not include the in-eclipse data, emphasizing that it was not part of the analysis. The sinusoidal modulation constructed from the coefficients fitted here is overplotted with a solid line and the filled circles represent the binned light curve. Figure 4 bottom panel shows the individual sinusoidal effects plotted using the fitted coefficients, including the beaming (red), ellipsoidal (blue), and reflection (green) effects. The solid line (black) is the fitted model, the sum of the three modulations. The bottom panel shows that the overall double peak shape of the folded light curve results from the ellipsoidal effect, the large difference between the two minima results from the reflection effect and the small difference between the two maxima is the signature of the beaming effect. This panel shows clearly that the beaming effect amplitude is much smaller than the other two, which is expected according to Figure 1, although it is detected beyond a 10σ significance (see Table 2).

4. DISCUSSION

Dilution of the light from the target with light from a nearby star, or stars, will act to decrease the observed amplitudes of the three effects. Therefore, before using the fitted coefficients to extract physical information about the star–planet system one needs to account for possible dilution of light. For KOI-13 the dilution is significant because the target is the brighter star, or stars, will act to decrease the observed amplitudes of every measurement and adding it to the model value of the subsequent point in the time series. The residual of the last measurement is added to the first point. Cyclic permutations keep the order of the residuals unchanged, preserving possible systematic trends, unlike random permutations. After analyzing all possible $10^4$ cyclic permutations, we examined the distributions of the resulting coefficients and took half the difference between the 84.13 and 15.87 percentiles to be the 1σ uncertainty. The coefficient’s distributions were highly symmetric about the median, and the latter were indistinguishable from the original fitted values. The errors derived this way were close to twice as large as the errors obtained directly from the linear least-squares method.

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Equation (1) gives

$$M_2 \sin i = \frac{0.37}{\alpha_{\text{beam}}} \left( \frac{M_1}{M_\odot} \right)^{2/3} \left( \frac{P_{\text{orb}}}{\text{day}} \right)^{1/3} \left( \frac{A_{\text{beam}}}{\text{ppm}} \right) M_J. \quad (6)$$

We calculate the right-hand side of Equation (6) using $P_{\text{orb}}$ derived here, an undiluted beaming amplitude of $A_{\text{beam}} = \Delta t_{15} = 9.32 \pm 0.86$ ppm, and a host star mass of $M_1 = 2.05 M_\odot$ from Szabo et al. (2011). We adopt a 10% uncertainty on the stellar mass since no error is given. The beaming coefficient is estimated to be $\alpha_{\text{beam}} = 0.73 \pm 0.03$ assuming the host star radiates as a blackbody with $T_{\text{eff}} = 8510 \pm 390$ K (Szabo et al. 2011), and by integrating over Kepler’s transmission spectrum. The resulting minimum mass for the companion is $M_2 \sin i = 9.2 \pm 1.1 M_J$. We note that a different estimate of $\Delta$, $M_1$, and $T_{\text{eff}}$ will result in a different $M_2 \sin i$.

Since this system is transiting, the above minimum mass is close to the true mass, and perhaps consistent with the latter
within the error bars. This puts the companion’s mass at the massive planet mass range.

As noted by Faigler & Mazeh (2011; see also Kilic et al. 2011), given sufficient information about the host star Equation (2) shows that \( A_{\text{ellip}} \) can be used to estimate another expression for the minimum mass, \( M_2 \sin^2 i \), and combined with \( M_2 \sin i \) estimated above the orbital inclination angle can be derived, which in turn allows one to derive \( M_2 \). This means that analysis of orbital photometry signals can, in principle, result in determining the companion’s true mass and not only the minimum mass. However, while Equation (1) describing the amplitude of the beaming effect is fairly accurate, Equation (2) describing the ellipsoidal effect amplitude is approximated (e.g., Morris 1985). It was shown by Pfahl et al. (2008) that the amplitude of this effect for an early-type star with no convective layer, like KOI-13, is difficult to describe analytically and it is likely far from the familiar expression used in Equation (2) (although the shape of the effect can still be described as a cosine at the first harmonic of the orbital period). Therefore, we do not proceed here with using \( A_{\text{ellip}} \) to derive \( M_2 \) and \( i \). The lack of an adequate equation for \( A_{\text{ellip}} \) does not allow us to use the ratio of the ellipsoidal and beaming amplitudes to check the likelihood of the model, as described by Faigler & Mazeh (2011).

The error bars derived for the fitted coefficients (see Table 2) show that the KOI-13 light curve is sensitive to modulations down to 2 ppm which can be detected at the 3\( \sigma \) level. Assuming white noise, the data from the entire 3.5 year Kepler mission lifetime can be sensitive to 1 ppm modulations for a target similar to KOI-13 in brightness and stellar noise. It is interesting to use these sensitivities to calculate the companion’s mass that can be identified for a range of orbital periods. To derive this predicted sensitivity of a search for orbital photometry signals in Kepler data, we adopt a signal-to-noise threshold that is a factor of two larger than the above, bringing it to 7\( \sigma \). Although our error bars were already inflated by a factor of two relative to the formal error bars (see Section 3), this additional factor of two is required in order to make the amount of false positives small enough considering the large number of light curves (e.g., Jenkins 2002). Such sensitivity diagrams are shown in Figure 5. The left panel is for a KOI-13-like host, and the right panel is for a Sun-like host at \( K_p = 12 \) mag. Only the beaming and ellipsoidal effects are plotted on these diagrams, since they are sensitive to the companion’s mass. The reflection effect is sensitive to the companion’s radius, which in turn is not sensitive to the companion’s mass in the mass range of gas giants and brown dwarfs. Left: assuming a KOI-13-like host (primary) star, and an amplitude of 2 ppm detected with Kepler data from the entire 3.5 year mission lifetime. Right: similar to the left panel, but for a Sun-like host star, at a brightness of \( K_p = 12 \) mag and assuming 5 ppm amplitude.

(A color version of this figure is available in the online journal.)

Figure 5. Minimum detectable secondary (star, brown dwarf, or planet) mass as a function of orbital period for a 7\( \sigma \) detection, and assuming an inclination angle of 60 deg. The reflection effect cannot be put on these diagrams, since its amplitude is sensitive to the companion’s radius, which in turn is not sensitive to the companion’s mass in the mass range of gas giants and brown dwarfs. Left: assuming a KOI-13-like host (primary) star, and an amplitude of 2 ppm detected with Kepler data from the entire 3.5 year mission lifetime. Right: similar to the left panel, but for a Sun-like host star, at a brightness of \( K_p = 12 \) mag and assuming 5 ppm amplitude.
otherwise will not affect its shape, resulting in underestimating the companion’s mass. All of the above points emphasize the need for RV follow-up to confirm BEER detections and measure the companion’s mass.

On a more positive note, the errors listed in Table 2 were obtained from an incomplete light curve, without the transit and occultation phases which cover ≈18% of KOI-13.01 orbit. Therefore, the results obtained here and the sensitivities shown in Figure 5 should be somewhat better for a non-transiting system similar to KOI-13.01, where the entire light curve is used, unless the system’s orientation is close to face-on.

Analysis of orbital photometry can, in principle, be used to look for additional signals, induced by additional objects in the system, including a possible second planet that is not necessarily transiting. This possibility is intriguing in light of the large number of candidate multi transiting planet systems found by Kepler (Lissauer et al. 2011), and the fact that about one sixth of the candidate transiting planetary systems contain more than a single transiting planet (Borucki et al. 2011). Latham et al. (2011) have shown that massive planets, such as KOI-13.01, are less likely to reside in multi transiting planet systems, although it is still possible that additional planets occupy non-transiting orbits.

Our periodogram presented in Figure 3 shows two small peaks, marked by dashed vertical lines, that are not associated with the 1.76 day orbital period. The strongest among the two corresponds to a period of 1.0600 ± 0.0010 days, and the smaller peak is at the first sub-harmonic. We verified that this secondary photometric signal, whose semi amplitude is 12 ppm, exists in each of the three Kepler quarters included in our analysis.

We investigated this further by subtracting the 1.76 day double harmonic model and applying the same period analysis as described above to the residuals. The derived fitted coefficients were $a_{1c}^{(2)} = 2.3 \pm 1.0$ ppm, $a_{1s}^{(2)} = 11.8 \pm 1.0$ ppm, and $a_{2s}^{(2)} = -3.1 \pm 0.5$ ppm, where the upper index is used for marking a secondary photometric signal. The sign of $a_{1c}^{(2)}$ and the relative size of the coefficients makes it unlikely that this signal originates from a second planet orbiting at 1.06 days.

The ratio between the 1.06 day period and the orbital period is 0.60100 ± 0.00072, which is close to an integer numbers ratio of 3:5. Assuming this is not a coincidence, it raises the possibility that the 1.06 day signal is a stellar pulsation triggered by the planetary companion. A similar scenario was suggested for WASP-33 (Collier Cameron et al. 2010), a planetary system that resembles KOI-13 as it includes a short-period (1.22 days) transiting planet orbiting a pulsating A-type star whose spin axis is misaligned with the planetary orbital axis (Collier Cameron et al. 2010; Barnes et al. 2011). An extreme example of pulsations induced by a binary companion is the KOI-54 binary system (Welsh et al. 2011), composed of two similar A-type stars on a highly eccentric orbit. Still, this scenario does not explain why we see a periodicity specifically at a relation of 3:5 with the orbit and not another integer relation.

We conclude that the true nature of this secondary photometric signal is currently not clear, although unlikely to be due to a second planet. In addition, we note that since the target is blended with a nearby star on Kepler CCDs, this secondary photometric signal could originate from the nearby star. A more detailed study of this signal, once more Kepler data become available, will be important for better understanding the possible false alarm scenarios of the application of the BEER approach to Kepler data, which have not been thoroughly studied yet.

Finally, we note that a close inspection of the phase folded light curve in Figure 4 top panel shows there are small deviations of the binned light curve from our double harmonic model. That model is simplistic, meant to be used only as a detection tool, and not as a detailed physical model, especially for data of such high quality. Therefore, the presence of these deviations should not be alarming, but rather be viewed as an opportunity for a more detailed study of bright systems using Kepler data.

5. SUMMARY

We have presented here a test case for analyzing orbital photometry using the BEER approach (Faigler & Mazeh 2011). We have shown that photometric measurements taken out of eclipse (transit and occultation) can be used to detect the presence of KOI-13.01, measure its orbital ephemeris and estimate its minimum mass. Therefore, similar non-transiting systems can be detected using Kepler data.

Moreover, we used the error bars derived for the fitted coefficients and a 7σ detection threshold to estimate the sensitivity of Kepler data for low-mass non-transiting companions. Assuming white noise, we showed that data accumulated during the entire 3.5 year Kepler mission lifetime will allow detection of low-mass short-period companions down to the few Jupiter mass level, for bright stars. In case the Kepler mission will be extended, this sensitivity will improve, allowing detection of lower mass companions, orbiting fainter stars at longer periods.

Spectra of hot stars of early spectral type like KOI-13 are not rich with deep and narrow absorption lines, which are used for measuring high-precision RVs. As a result, those stars are not regularly monitored by RV surveys, leading in turn to highly limited knowledge about their low-mass companion population. Analysis of the orbital photometry signal presents an opportunity to extend our knowledge about low-mass companions to early-type host stars, especially considering that they show a decreased amount of stellar activity. For example, orbital photometry can be used to test the suggestion of Bouchy et al. (2011) that massive planets and brown dwarfs are more frequent around F-type stars than G-type stars, and see whether this trend continues into A-type stars. RV confirmation of such companions, detected through orbital photometry, will probably be difficult or even impossible (For an RV confirmation of a white dwarf companion detected through orbital photometry, see Ehrenreich et al. 2011). However, a detection of a large sample along with an improved understanding of the false positive scenarios will allow a statistical analysis and a comparison to the characteristics of the companion population orbiting Sun-like stars.

The analysis done here uses only out of eclipse data. Several authors have already shown that Kepler’s continuous and high-precision photometry taken in-eclipse can be used for additional characterization of the companion’s orbit (Barnes 2009; Barnes et al. 2011; Shporer et al. 2011; Groot 2011; Szabo et al. 2011). These authors show that small asymmetries in the eclipse light curve can be used for measuring the sky-projected spin-orbit angle (the angle between the star’s rotation axis and the companion’s orbital angular momentum axis), thereby showing the high scientific potential of using photometry, out and in eclipse, to study binary systems, those with low-mass companions in particular.
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Facility: Kepler

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