SEVEN NEW BINARIES DISCOVERED IN THE KEPLER LIGHT CURVES THROUGH THE BEER METHOD CONFIRMED BY RADIAL VELOCITY OBSERVATIONS

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ABSTRACT

We present seven newly discovered non-eclipsing short-period binary systems with low-mass companions, identified by the recently introduced BEER algorithm, applied to the publicly available 138-day photometric light curves obtained by the Kepler mission. The detection is based on the beaming effect (sometimes called Doppler boosting), which increases (decreases) the brightness of any light source approaching (receding from) the observer, enabling a prediction of the stellar Doppler radial velocity (RV) modulation from its precise photometry. The BEER algorithm identifies the BEaming periodic modulation, with a combination of the well-known Ellipsoidal and Reflection/heating periodic effects, induced by short-period companions. The seven detections were confirmed by spectroscopic RV follow-up observations, indicating minimum secondary masses in the range 0.07–0.4 M☉. The binaries discovered establish for the first time the feasibility of the BEER algorithm as a new detection method for short-period non-eclipsing binaries, with the potential to detect in the near future non-transiting brown-dwarf secondaries, or even massive planets.

Key words: binaries: spectroscopic – brown dwarfs – methods: data analysis – planets and satellites: detection

Online-only material: color figures

1. INTRODUCTION

In a recent paper, Faigler & Mazeh (2011) presented a new way to discover short-period non-eclipsing binaries with low-mass companions by using highly precise photometric light curves obtained by space missions such as CoRoT and Kepler (Rouan et al. 1998; Baglin et al. 2006; Borucki et al. 2010). The algorithm, BEER, based on an idea suggested by Loeb & Gaudi (2003) and Zucker et al. (2007), searches for the beaming effect, sometimes called Doppler boosting, induced by stellar radial motion. This effect causes an increase (decrease) of the brightness of any light source approaching (receding from) the observer (Rybicki & Lightman 1979), on the order of $4v_r/c$, where $v_r$ is the radial velocity (RV) of the source and $c$ is the velocity of light. Therefore, periodic modulation of the stellar velocity due to a companion in a binary orbit will produce a corresponding periodic beaming modulation of the stellar photometry.

For short-period binaries the beaming effect is extremely small, on the order of 100–300 ppm (parts per million). Therefore the effect has become relevant only recently, when CoRoT and Kepler—the two presently operating satellites that search for transiting exoplanets—started producing hundreds of thousands of uninterrupted light curves with high precision (Auvergne et al. 2009; Koch et al. 2010).

As predicted, several studies detected the beaming effect in eclipsing binaries and transiting planets, for which the orbital period was well established from the space-obtained light curves (van Kerkwijk et al. 2010; Rowe et al. 2010; Carter et al. 2010; Mazeh & Faigler 2010; Bloemen et al. 2011; Kipping & Spiegel 2011). Yet, space mission data can yield much more. Evidence of the binarity of a stellar system can be found from detecting the beaming effect without any eclipse or transit (Loeb & Gaudi 2003; Zucker et al. 2007). However, the beaming modulation by itself might not be enough to render a star a good binary candidate, as periodic modulations could be produced by other effects, stellar variability in particular (Aigrain et al. 2004).

The BEER detection algorithm (Faigler & Mazeh 2011), therefore, searches for stars that show in their light curves a combination of the BEaming effect with two other effects induced by the presumed companion—the Ellipsoidal and the Reflection modulation. The ellipsoidal variation (Morris 1985) is due to the tidal distortion of each component by the gravity of its companion (see a review by Mazeh 2008), while the reflection/heating variation (referred to herein as the reflection modulation) is induced by the luminosity of each component that falls only on the close side of its companion (Vaz 1985; Wilson 1990; Maxted et al. 2002; Harrison et al. 2003; For et al. 2010; Reed et al. 2010). Detecting the beaming effect together with the ellipsoidal and reflection modulations, with the expected relative amplitudes and phases in particular, can suggest the presence of a small non-transiting companion.

Just as in transit searches, the candidates found by the BEER algorithm have to be followed by RV observations in order to confirm the existence of the low-mass companion and to reject other possible interpretations of the photometric modulation.

This paper presents the discovery of the first seven new binaries with low-mass secondaries, in the range 0.07–0.4 M☉, detected by using the BEER algorithm and confirmed by RV spectroscopic follow-up measurements. Section 2 presents the photometric analysis of the Kepler light curves, Section 3 provides the details and results of the RV observations, Section 4 summarizes and compares the results of the photometric analysis and the RV measurements, and Section 5 discusses the implications of, and conclusions from, the findings of this paper.

2. PHOTOMETRIC ANALYSIS

We used the publicly available Kepler raw light curves of the Q0, Q1, and Q2 quarters, spanning 138 days. To avoid...
Figure 1. Light curves of the seven detections, after outlier removal and long-term detrending. Top to bottom: K10848064, K08016222, K09512641, K07254760, K05263749, K04577324, and K06370196. For clarity, each light curve was shifted by 5000 ppm relative to the previous one. The periodic modulation can be seen in all seven light curves. The light curves show several discontinuities: end of Q0 at day 131, end of Q1 around day 166, Q2 first safe mode event at day 183, and Q2 second safe mode event at day 232. In addition there is a single discontinuity at day 155 in the K05263749 light curve. (A color version of this figure is available in the online journal.)

Table 1

Coordinates, Magnitudes, Stellar Properties, and Photometric Analysis Results of the Seven Candidates

|                  | K10848064 | K08016222 | K09512641 | K07254760 | K05263749 | K04577324 | K06370196 |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| R.A.             | 19:01:21.24 | 19:06:48.03 | 18:58:39.91 | 18:42:28.78 | 19:12:59.00 | 19:42:35.91 | 19:35:00.36 |
| Decl.            | 48:16:32.90 | 43:48:32.90 | 46:08:52.80 | 42:49:31.90 | 40:26:42.30 | 39:38:00.80 | 41:47:59.60 |
| Kp (mag)         | 12.13      | 11.65      | 11.66      | 12.04      | 11.53      | 11.98      | 11.97      |
| Ra (R⊙)          | 1.5        | 1.3        | 1.7        | 1.5        | 1.9        | 1.3        | 2.1        |
| Mb (M⊙)          | 1.2        | 1.1        | 1.2        | 1.2        | 1.3        | 1.2        | 1.3        |
| Photometry results |          |           |           |           |           |           |           |
| Period (days)    | 3.49 ± 0.01 | 5.60 ± 0.02 | 4.65 ± 0.02 | 2.66 ± 0.01 | 3.73 ± 0.01 | 2.33 ± 0.01 | 4.23 ± 0.01 |
| Ellipsoidal (ppm)| 201 ± 3    | 30 ± 2     | 172 ± 10   | 845 ± 7    | 1222 ± 5   | 1489 ± 4   | 1210 ± 10  |
| Beaming (ppm)    | 118 ± 3    | 97 ± 2     | 185 ± 5    | 356 ± 6    | 358 ± 5    | 436 ± 4    | 382 ± 7    |
| Reflection (ppm) | 0 ± 3      | 6 ± 2      | 36 ± 4     | 150 ± 6    | 158 ± 5    | 245 ± 4    | 174 ± 7    |
| Cleaned data rms (ppm) | 204 | 106 | 227 | 807 | 1184 | 1408 | 1141 |
| Residuals rms (ppm) | 128  | 68 | 113 | 268 | 200 | 168 | 328 |

Notes.

a From Kepler Input Catalog.
b Calculated from Kepler Input Catalog log $g$ and $R$.

d systematic variations, we ignored all data points within 1 day after the beginning of Q2, and all data points within 1 day before, to 3 days after, each of the two safe mode events in Q2. We also corrected two systematic jumps at Kepler time (JD − 2,454,833) of 200.32 and 246.19 days. We then applied the BEER algorithm to 14,685 stars brighter than 13th mag, with Kepler Input Catalog (Brown et al. 2011) radius smaller than 3 R⊙, calculating the BEER periodogram (Faigler & Mazeh 2011) with period range of 0.5–20 days for each star. Next, we identified the periodograms whose highest peak was at least three times higher than the next highest one. For these stars we used the peak period to estimate the system secondary mass and radius, assuming the periodicity is induced by a secondary star. We then selected 25 candidates with secondary mass smaller than 0.5 M⊙ and implied albedo smaller than 0.4, suggesting a significant probability for a low-mass companion. These candidates were then followed by RV observations, which we describe in detail in the next section. In a forthcoming paper, we will report on the false alarm cases and analyze the false alarm frequency of our candidates. Here, we report on the first seven clear detections.

Table 1 lists for each of the seven stars its coordinates, the stellar properties estimates from the Kepler Input Catalog (Brown et al. 2011), the photometric periods and amplitudes...
We order the stars according to the detected RV amplitude, presented in the next section. Figure 1 presents the “cleaned” (Mazeh & Faigler 2010; Faigler & Mazeh 2011) photometric data of the seven detections, Figure 2 presents the BEER periodograms for the detections, and Figure 3 shows the light curves folded with the detected period. In fact, the quality of the Kepler data is so high that the periodic modulation can be seen...
directly from the cleaned data, plotted in Figure 1, even without consulting the BEER periodogram.

It is interesting to compare the shape of the BEER modulation of the seven candidates, presented in Figure 3. In six of them the two peaks, at phase of 0.25 and 0.75, are similar, although the latter is somewhat smaller, due to the beaming effect (Faigler & Mazeh 2011). In one case, K08016222, the second peak completely disappeared, because in this case the beaming amplitude is more than three times higher than that of the ellipsoidal, while for the rest of the candidates the ellipsoidal amplitude is significantly higher than the beaming amplitude. This is a clear result of the long orbital period and small stellar radius of this system, relative to the other systems, since the ellipsoidal amplitude to beaming amplitude ratio is proportional to $R_\star^3/P_{\text{orb}}^{5/3}$ (Faigler & Mazeh 2011; Zucker et al. 2007).
The RV observations were performed between 2010 September 25 and 2011 June 15 with the Tillinghast Reflector Echelle Spectrograph (TRES; Fürész 2008) mounted on the 1.5 m Tillinghast Reflector at the Fred Lawrence Whipple Observatory operated by the Smithsonian Astrophysical Observatory on Mount Hopkins in Southern Arizona, using the medium fiber at a spectral resolution of 44,000, covering a spectral range from 385 to 910 nm. Exposures of a thorium–argon hollow-cathode lamp immediately before and after each exposure were used for wavelength calibration. The spectra were extracted and rectified to intensity versus wavelength using standard procedures.

To derive precise relative radial velocities, we performed a cross-correlation between each observed spectrum and a template spectrum constructed by shifting and co-adding all the observed spectra. In addition to the template constructed by shifting and co-adding all the observed spectra, we also tried using the strongest individual exposure of each object as the observed template. The two approaches gave essentially indistinguishable results, with slightly better residuals from the orbital fits for the shifted and co-added template. We also derived absolute velocities using the library of synthetic templates and found the same orbits, although with somewhat larger residuals.

We did not include spectral orders that were significantly contaminated by telluric lines from Earth’s atmosphere, nor did we include the bluest orders with the lowest signal-to-noise ratio and a few red orders with known problems. The error of each relative velocity was estimated using the standard deviation of the velocities from the 21 individual orders, but the velocities themselves were derived by first co-adding the correlation functions from the 21 orders to get a natural weighting of the contribution from each order.

Using the shifted and co-added template can distort the cross-correlation peak because the noise in each spectrum correlates with the same noise that is still present in the averaged template, and therefore can lead to underestimated uncertainties of the velocities. To correct this effect we later inflated the uncertainties of the orbital elements (see $\chi^2_{red}$ discussion below).

We used a library of synthetic spectra, calculated by John Laird for a grid of Kurucz model atmospheres, using a line list developed by Jon Morse (Carney et al. 1987; Latham et al. 2002), to estimate values for the effective temperature, surface gravity, metallicity, and rotational velocity of the seven primaries. This was done by cross-correlating each co-added observed template spectrum against a grid of synthetic templates surrounding the one that gave the best correlation. Our library of synthetic spectra has a spacing of 250 K in effective temperature, $T_{\text{eff}}$; 0.5 in log surface gravity, log $g$; 0.5 in the log of the metallicity compared to the Sun, [m/H]; and has a progressive spacing for rotational velocity, $v_{\text{rot}}$. Because the grid is coarse, we used the correlation peak heights to interpolate between grid points to arrive at a more precise classification. Three TRES spectral orders overlap with the synthetic spectra, so we performed this cross-correlation and interpolation in each order. The mean values, weighted by the cross-correlation peak height in each order, and rms errors are reported in Table 2. Note that because of the degeneracies between $T_{\text{eff}}$, log $g$, and [m/H] in the stellar spectra, correlated systematic errors may dominate. For this reason, and based on our experience in other surveys, we have inflated the errors by adding 100 K in $T_{\text{eff}}$ and 0.1 dex in log $g$ and [m/H] in quadrature to the formal order-to-order rms errors.

The relative velocities were adjusted by a constant offset to a system of absolute velocities using observations of the nearby IAU Radial Velocity Standard Star HD 182488, whose absolute velocity was assumed to be $-21.508 \text{ km s}^{-1}$. This adjustment utilized our library of synthetic templates, from which we picked the synthetic template that gave the best match to the observations of each star in the spectral order centered on the Mg b feature near 518 nm. This approach should avoid the problem of possible template mismatch between the various target stars and HD 182488. The uncertainty in the zero point of our absolute velocities is probably limited by the uncertainty in the absolute velocity of HD 182488, which could be as large as 100 m s$^{-1}$.

Table 3 lists the RV measurements and their uncertainties.

For all seven candidates discussed here the first RV measurements showed clear variability. We therefore obtained enough RVs to allow orbital solutions completely independent of the BEER analysis. To determine the orbital elements of each target, independent of the BEER results, we ran a Markov Chain Monte Carlo (MCMC) analysis of the radial velocities. We adopted values for the epoch ($T$), period ($P$), systemic velocity ($\gamma$), orbital semi-amplitude ($K$), eccentricity ($e$), and argument of periastron ($\omega$) corresponding to the median values of the posterior distributions. The errors listed in the tables are those corresponding to the 16th and 84th percentiles of the posterior distributions. The reported error on $\gamma$, however, includes contributions both from the formal error from the MCMC posterior and from the uncertainty in the TRES absolute zero-point offset.

When the orbit is circular, the epoch reported is $T_{\text{max}}$, the time of maximum velocity, and when the orbit is eccentric, we report $T_{\text{peri}}$, the time of periastron passage. In six of the seven cases, either the orbital phase coverage was not sufficient to adequately constrain the eccentricity or $e$ was statistically indistinguishable from zero. In these cases, we fixed $e = 0$ and reran the MCMC chains, adopting $T_{\text{max}}$, $P$, $\gamma$, and $K$ from this solution. In one case, K08016222, the orbital phase coverage is good and $e$ is significantly non-zero.

Figure 4 shows the RV follow-up measurements for each of the seven binaries, folded with the period found, and Table 4 lists the orbital elements derived. The table also lists $\chi^2_{\text{red}}$, the reduced $\chi^2$ of the model, and the time span of the observations. For two binaries the derived $\chi^2_{\text{red}}$ value is close to unity, as expected, but for the others its value is relatively large. This
### Table 3
Radial Velocities of the Seven Binaries

| Time (HJD − 2,455,000) | RV (m s$^{-1}$) | σ (m s$^{-1}$) | Time (HJD − 2,455,000) | RV (m s$^{-1}$) | σ (m s$^{-1}$) |
|------------------------|------------------|----------------|------------------------|------------------|----------------|
| K10848064:             |                  |                | K07254760:             |                  |                |
| 464.710256             | −8835            | 119            | 694.814729             | 37083            | 39             |
| 469.624378             | −17974           | 76             | 695.834208             | −11894           | 46             |
| 488.634305             | −16743           | 77             | 697.807122             | 15727            | 61             |
| 489.574441             | −6552            | 123            | 699.779976             | 46148            | 83             |
| 490.617670             | −17742           | 83             | 702.796583             | 36412            | 47             |
| 498.599389             | −23508           | 57             | 703.815335             | −11560           | 54             |
| 513.639601             | −9108            | 170            | 704.796619             | 39179            | 51             |
| 692.888788             | −13130           | 124            | 705.802918             | 14063            | 89             |
| 722.832949             | −14423           | 43             |                        |                  |                |
| 723.863233             | −7328            | 56             |                        |                  |                |
| 724.857438             | −21205           | 28             |                        |                  |                |
| K08016222:             |                  |                |                        |                  |                |
| 465.787007             | −31819           | 63             | 694.829973             | 20947            | 69             |
| 466.631973             | −37012           | 39             | 696.825053             | 13787            | 141            |
| 467.723417             | −33482           | 96             | 697.826976             | 45095            | 68             |
| 469.613641             | −18312           | 42             | 699.974074             | −12159           | 61             |
| 485.603938             | −23367           | 37             | 701.980887             | 34841            | 87             |
| 490.579108             | −29588           | 63             | 705.958593             | 23622            | 73             |
| 498.591317             | −22720           | 47             | 722.851562             | 10492            | 63             |
| 722.843084             | −21815           | 86             | 723.875349             | 45267            | 46             |
| K09512641:             |                  |                | 724.846275             | 10122            | 75             |
| 658.935318             | 6324             | 22             |                        |                  |                |
| 669.855208             | 33915            | 29             |                        |                  |                |
| 693.803705             | 34608            | 67             | 703.971684             | 38803            | 87             |
| 694.822698             | 16733            | 54             | 722.871612             | 46652            | 99             |
| 696.815346             | 17503            | 50             | 723.895443             | −22140           | 103            |
| 697.816773             | 34761            | 48             | 724.869757             | 34694            | 124            |
| 698.934501             | 27404            | 39             | 726.867639             | 5528             | 96             |
| 701.814582             | 24838            | 40             | 727.847462             | 33003            | 91             |
| 702.805990             | 36143            | 39             |                        |                  |                |
| 703.826109             | 22562            | 59             |                        |                  |                |
| 704.813460             | 6060             | 65             |                        |                  |                |
| 705.813161             | 11855            | 43             |                        |                  |                |

### Table 4
Orbital Model Elements of the Seven Binaries

| K10848064 | K08016222 | K09512641 | K07254760 | K05263749 | K04577324 | K06370196 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $T_{\text{max}} - 2,455,000$ (HJD) | 465.1289  | 464.6288  | 642.3690  | 702.4395  | 466.7071  | 466.7005  | 698.8374  |
| $\pm 0.0060$       | $\pm 0.0029$ | $\pm 0.0052$ | $\pm 0.0126$ | $\pm 0.0124$ | $\pm 0.0079$ | $\pm 0.0035$ |
| $P$ (days)       | 3.49318   | 5.60864   | 4.64588   | 2.65642   | 3.72665   | 2.32863   | 4.23371   |
| $\pm 0.00099$    | $\pm 0.00017$ | $\pm 0.00044$ | $\pm 0.00068$ | $\pm 0.00019$ | $\pm 0.000070$ | $\pm 0.000067$ |
| $\gamma$ (km s$^{-1}$) | $-15.670$  | $-28.078$  | $20.518$  | $17.092$  | $13.862$  | $11.325$  | $-17.168$  |
| $\pm 0.219$      | $\pm 0.048$ | $\pm 0.110$ | $\pm 0.177$ | $\pm 0.060$ | $\pm 0.119$ | $\pm 0.454$ |
| $\mathcal{K}$ (km s$^{-1}$) | 9.107      | 9.495      | 15.519    | 29.024    | 31.428    | 35.316    | 40.222     |
| $\pm 0.073$      | $\pm 0.018$ | $\pm 0.023$ | $\pm 0.061$ | $\pm 0.040$ | $\pm 0.043$ | $\pm 0.131$ |
| $e$               | 0 (fixed)  | 0.0439     | 0 (fixed)  | 0 (fixed)  | 0 (fixed)  | 0 (fixed)  | 0 (fixed)  |
| $\omega$ (deg)   | $36.2 \pm 2.6$ | $36.2 \pm 2.6$ | $36.2 \pm 2.6$ | $36.2 \pm 2.6$ | $36.2 \pm 2.6$ | $36.2 \pm 2.6$ |
| $\chi^2_{\text{red}}$ | 11.0       | 1.0        | 4.3        | 11.6       | 2.6        | 1.2        | 12.6       |
| Span (days)       | 260.1      | 257.1      | 46.9       | 11.0       | 30.0       | 31.9       | 32.9       |

**Note.** For K08016222 the $T_{\text{max}}$ value is the time of periastron passage.
could indicate either that for those binaries our RV uncertainties are underestimated, or that our RV model is too simple, due to some stellar noise, for example. In order to get more realistic uncertainties for the model elements, we inflated the parameter uncertainties of each target by its $\sqrt{\chi^2_{\text{red}}}$, which is equivalent to inflating the RV errors of that star by the same factor. The resulting uncertainties in the orbital model elements are listed in Table 4.
Table 5
Derived Photometric RV Period and Semi-amplitude Together with RV Observations Period and Semi-amplitude for Each of the Seven Binaries

| K10848064 | K08016222 | K09512641 | K07254760 | K05263749 | K04577324 | K06370196 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Photometry results: | | | | | | |
| Period (days) | 3.49 ± 0.01 | 5.60 ± 0.02 | 4.65 ± 0.02 | 2.66 ± 0.01 | 3.73 ± 0.01 | 2.33 ± 0.01 | 4.23 ± 0.01 |
| \(\alpha_{\text{beam}}\) (km s\(^{-1}\)) | 9.37 ± 0.34 | 7.19 ± 0.22 | 15.21 ± 0.72 | 28.97 ± 0.89 | 29.14 ± 0.81 | 36.86 ± 1.10 | 30.61 ± 1.12 |
| RV results: | | | | | | |
| \(N_{\text{obs}}\) | 11 | 8 | 12 | 8 | 9 | 8 | 8 |
| Period (days) | 3.49318 ± 0.00099 | 5.60864 ± 0.00017 | 4.64588 ± 0.00044 | 2.65642 ± 0.00068 | 3.72665 ± 0.00019 | 2.328663 ± 0.000070 | 4.23371 ± 0.000067 |
| \(K_{\text{RV}}\) (km s\(^{-1}\)) | 9.107 ± 0.073 | 9.495 ± 0.018 | 15.519 ± 0.023 | 29.024 ± 0.061 | 31.428 ± 0.040 | 35.316 ± 0.043 | 40.223 ± 0.131 |
| Minimum secondary mass (\(M_{\text{up}}\)) | 76 ± 5 | 90 ± 6 | 147 ± 10 | 222 ± 15 | 279 ± 19 | 253 ± 17 | 376 ± 25 |

4. RESULTS

Table 5 lists for each of the seven newly discovered binaries the period derived from the photometry, the calculated \(\alpha_{\text{beam}}\), the expected RV semi-amplitude, \(K_{\text{beam}}\), derived from \(\alpha_{\text{beam}}\), and the photometric beaming amplitude. The \(\alpha_{\text{beam}}\) factor includes one component that originates from the fact that the stellar spectrum is Doppler shifted relative to the observed band. To estimate this factor for each of the seven detected binaries we numerically shifted spectra from the library of Castelli & Kurucz (2004) models that were close to the estimated temperature, metallicity, and gravity of each of the seven stars. The values adopted were derived by interpolation of the \(\alpha_{\text{beam}}\) values between the available models of the library. The \(\alpha_{\text{beam}}\) uncertainties were estimated by calculating the interpolated \(\alpha_{\text{beam}}\) values within the \(T_{\text{eff}}, \log g, \text{ and } [\text{m/H}]\) error ranges. The error on the expected \(K_{\text{beam}}\) was estimated by combining the photometric beaming amplitude error and the \(\alpha_{\text{beam}}\) error. The table then reports the number of RV measurements, their derived RV period and semi-amplitude, and the minimal secondary mass, up to \(\sin i\). For all cases we independently derived the period of the RV modulation, and found it to be consistent with the photometric period, indicating that the orbital period was reliably derived by the BEER algorithm, solely from the photometric data.

In six of the binaries the eccentricity was too small to be derived significantly, so we assumed circular orbits. Because these are short-period stellar binaries, the expected circularization timescale is short, so finding in most cases that \(e = 0\) is consistent with our expectations. For K08016222 we find \(e = 0.0439 ± 0.0022\). Interestingly, this is the binary with the longest period, so its lifetime might have been too short to achieve circularization (Mathieu & Mazeh 1988).

Out of the seven binaries, the measured RV amplitudes of five cases were consistent with those predicted by the photometric analysis. For the other two stars, K08016222 and K06370196, the predicted amplitudes were 24% smaller than the observed ones. This could be due to underestimation of the photometric amplitude. Another possible explanation may be an inaccurate translation of the photometric amplitude to the expected RV amplitude, which depends on the assumed stellar spectral type. We need more confirmed binaries to understand this effect.

5. DISCUSSION

The RV observations presented here demonstrate the ability of the BEER algorithm to discover short-period binaries with minimum secondary masses in the range 0.07–0.4 \(M_{\odot}\) in the publicly available Kepler data.

The original goal of the Kepler and CoRoT missions was to search for transiting planets. Such projects are limited to planets with orbital inclinations close to 90°. The serendipitous discoveries of eclipsing binaries in the Kepler photometry (Prša et al. 2011) are suffering from the same limitation. The BEER algorithm, on the other hand, is searching for non-transiting companions, and therefore can detect many more systems with much lower inclination angles. Searching with BEER is effectively equivalent to performing an RV survey that is not limited to nearly face-on inclinations. Applying the BEER algorithm to the hundreds of thousands of already available light curves of Kepler and CoRoT is like performing an RV survey of a huge sample that is composed of these stars.

Therefore, we expect BEER to discover many hundreds of new binaries with short periods. Furthermore, whereas in RV studies the actual mass of the companion depends on the unknown inclination angle, detecting both the ellipsoidal and the beaming effects will enable BEER to derive, or at least estimate, the mass of the small companion in certain cases. As pointed out by Faigler & Mazeh (2011), this can become possible because the two effects have different dependencies on the orbital inclination, and therefore the derived ratio of the amplitudes of the two effects can, in principle, remove the degeneracy between the secondary mass and the inclination.

Obviously, at this stage of the BEER search, detecting a candidate is not enough—the candidates have to be confirmed by follow-up RV observations. However, when we accumulate enough observations we will be able to estimate the false alarm probability, which might be a function of the amplitude of the photometric modulation and the stellar mass, radius, and temperature. Therefore, we will be able to derive the statistical features of the short-period binaries without confirming each detection with RV observations.

The seven cases presented here were based on the Kepler Q0–Q2 data. Faigler & Mazeh (2011) suggested that once the full Kepler data set is available, we should be able to detect brown-dwarf secondaries and even massive planets. Moreover, the other stellar modulations that contribute now to the false alarm frequency are not expected to be so stable on timescales of years, whereas the three BEER effects are strictly periodic and stable. Therefore, we expect the false alarm frequency to decrease when we have access to longer data sets. The
unprecedentedly large sample size and data quality, together with a knowledge of the false alarm probability, could serve as a tool to study accurately the frequency of low-mass secondaries in short-period binaries on the high- and low-mass ends of the brown-dwarf desert (Raghavan et al. 2010; Udry 2010; Sahlmann et al. 2011).

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