ABSTRACT

We present the first case in which the BEER algorithm identified a hot Jupiter in the Kepler light curve, and its reality was confirmed by orbital solutions based on follow-up spectroscopy. The companion Kepler-76b was identified by the BEER algorithm, which detected the BEaming (sometimes called Doppler boosting) effect together with the Ellipsoidal and Reflection/emission modulations (BEER), at an orbital period of 1.54 days, suggesting a planetary companion orbiting the 13.3 mag F star. Further investigation revealed that this star appeared in the Kepler eclipsing binary catalog with estimated primary and secondary eclipse depths of $5 \times 10^{-3}$ and $1 \times 10^{-4}$, respectively. Spectroscopic radial velocity follow-up observations with Tillinghast Reflector Echelle Spectrograph and SOPHIE confirmed Kepler-76b as a transiting 2.0 $\pm$ 0.26 $M_{\text{Jup}}$ hot Jupiter. The mass of a transiting planet can be estimated from either the beaming or the ellipsoidal amplitude. The ellipsoidal-based mass estimate of Kepler-76b is consistent with the spectroscopically measured mass while the beaming-based estimate is significantly inflated. We explain this apparent discrepancy as evidence for the superrotation phenomenon, which involves eastward displacement of the hottest atmospheric spot of a tidally locked planet by an equatorial superrotating jet stream. This phenomenon was previously observed only for HD 189733b in the infrared. We show that a phase shift of 10.3 $\pm$ 2.0 of the planet reflection/emission modulation, due to superrotation, explains the apparently inflated beaming modulation, resolving the ellipsoidal/beaming amplitude discrepancy. Kepler-76b is one of very few confirmed planets in the Kepler light curves that show BEER modulations and the first to show superrotation evidence in the Kepler band. Its discovery illustrates for the first time the ability of the BEER algorithm to detect short-period planets and brown dwarfs.

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

Online-only material: color figures

1. INTRODUCTION

CoRoT and Kepler have produced hundreds of thousands of nearly uninterrupted high-precision light curves (Auvergne et al. 2009; Koch et al. 2010) that enable detection of minute astrophysical effects. One of these is the beaming effect, sometimes called Doppler boosting, induced by stellar radial velocity (RV). The effect causes a decrease (increase) of the brightness of any light source receding from (approaching) the observer (Rybicki & Lightman 1979) on the order of $4v_t/c$, where $v_t$ is the RV of the source and $c$ is the velocity of light. Thus, periodic variation of the stellar RV due to an orbiting companion produces a periodic beaming modulation of the stellar flux. Loeb & Gaudi (2003) and Zucker et al. (2007) suggested using this effect to identify non-eclipsing binaries and exoplanets in the light curves of CoRoT and Kepler. The precision of the two satellites is needed because even for short-period binaries with large RV orbital amplitudes, the beaming effect is small, on the order of 100–500 ppm (parts per million).

As predicted, several studies identified the beaming effect in short-period known eclipsing binaries (van Kerkwijk et al. 2010; Rowe et al. 2011; Carter et al. 2011; Kipping & Spiegel 2011; Bloemen et al. 2011, 2012; Breton et al. 2012). Yet, space missions data can be used to identify non-eclipsing binaries through detection of the beaming effect (Loeb & Gaudi 2003; Zucker et al. 2007). However, the beaming modulation by itself might not be enough to identify a binary star, as periodic modulations could be produced by other effects, stellar variability in particular (e.g., Aigrain et al. 2004).

To overcome this problem, the BEER algorithm (Faigler & Mazeh 2011) searches for stars that show in their light curves a combination of the BEaming effect with two other effects that are produced by a short-period companion—the Ellipsoidal and the Reflection modulations. The ellipsoidal variation (e.g., Morris 1985) is due to the tidal interaction between the two components (see a review by Mazeh 2008), while the reflection/heating variation (referred to herein as the reflection modulation) is caused by the luminosity of each component that falls on the facing half of its companion (e.g., 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 periodic variations, with the expected relative amplitudes and phases, can indicate the presence of a small non-eclipsing companion. Recently, Faigler et al. (2012) reported RV confirmation of seven new non-eclipsing short-period binary systems in the Kepler field, with companion minimum masses in the range 0.07–0.4 $M_{\odot}$, that were discovered by the BEER algorithm.

For brown dwarfs or planetary companions the beaming effect is even smaller, on the order of 2–50 ppm. Interestingly, several studies were able to detect this minute effect in systems with transiting brown dwarfs and planets (Mazeh & Faigler 2010; Shporer et al. 2011; Mazeh et al. 2012; Jackson et al. 2012; Mislis et al. 2012; Barclay et al. 2012), indicating it may be
possible to detect such non-transiting objects by identifying these effects in their host star light curves.

This paper presents the discovery of Kepler-76b, the first hot Jupiter detected by the BEER algorithm that was subsequently confirmed by Tillinghast Reflector Echelle Spectrograph (TRES) and SOPHIE RV spectroscopy. It was identified by the BEER algorithm as a high-priority planetary candidate. Visual inspection of its light curve revealed a V-shaped primary transit and a minute secondary eclipse, combined with beaming, ellipsoidal, and reflection amplitudes, consistent with a massive-planet companion. We noticed later that this star was beaming, ellipsoidal, and reflection amplitudes, consistent with a minute secondary eclipse, combined with the BEER algorithm as a high-priority planetary candidate. 

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Table 1

| R.A.        | Decl.       | Right ascension | Declination |
|-------------|-------------|-----------------|-------------|
| 19:36:46.11 | 39:37:08.4  |                 |             |

| $K_T^a$ (mag) | $T_{\text{eff}}^a$ (K) | $T_{\text{eff}}^b$ (K) | log $g^c$ (dex) |
|--------------|-------------------------|-------------------------|-----------------|
| 13.3         | 6196                    | 6409 ± 95               | 4.388           |

| [(H/Fe)]$^d$ (dex) | $R_*$ (R$_\odot$) | $M_*$ (M$_\odot$) | $f_3^e$ |
|-------------------|-------------------|-------------------|---------|
| −0.033            | 1.12              | 1.12              | 0.056   |

| BEER model:       | With transit and occultation points masked out | Orbital period | Ellipsoidal semi-amplitude |
|-------------------|---------------------------------------------|----------------|---------------------------|
| Period (days)     | 1.5449 ± 0.0007                            | 73.49 ± 0.19   | 21.5 ± 1.7               |
| $T_0 - 2455000^b$ (BJD) | 73.49 ± 0.19                           | 15.6 ± 2.2     | 56.0 ± 2.5               |
| Ellipsoidal (ppm)$^b$ | 15.6 ± 2.2                                   | 56.0 ± 2.5     | 133                      |
| Beaming (ppm)$^b$  | 15.6 ± 2.2                                    | 56.0 ± 2.5     | 127                      |

Notes.

$^a$ From Kepler Input Catalog.

$^b$ Revised $T_{\text{eff}}$ from Pinsonneault et al. (2012).

$^c$ Calculated from Kepler Input Catalog log $g$ and $R$.

$^d$ $T_0$ is the time in which the companion is closest to the observer, assuming a circular orbit.

$^e$ Corrected for third light.
Figure 1. Light curve of Kepler-76 for a selected time span of 37 days, after outlier removal and long-term detrending. Top: the untruncated light curve, showing the full depth of the transits. Bottom: the light curve with the core of the transit events truncated. Note the different scales of the two plots. (The transit missing at time 780.9 fell in a short gap in the raw data.)

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

Figure 2. FFT-based power spectrum of the detection. The orbital period and half-orbital period peaks are marked by vertical dashed lines. For clarity, only the frequency range of 0–1.5 day$^{-1}$ is plotted, since no significant peak was found for frequencies higher than 1.5 day$^{-1}$.

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

(2012), and the results of the BEER analysis. Figure 1 presents a short section of the “cleaned” (Mazeh & Faigler 2010; Faigler & Mazeh 2011) photometric data of the host star, Figure 2 presents the FFT-based power spectrum, and Figure 3 shows the light curve folded with the detected period. It is interesting to note, by inspecting the cleaned light curves (Figure 1) and the data and residuals rms (Table 1), that the effects are significantly smaller than the light curve noise, to the point that the detected modulations almost cannot be recognized by eye. However, deriving the BEER photometric power spectrum from data with
time spans of hundreds of days produces a prominent detectable peak at the orbital period (Figure 2).

3. SPECTROSCOPIC OBSERVATIONS

Spectroscopic observations of the candidate were obtained between May 29 and 2012 October 6 with the TRES (Furész 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 resolution 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 developed by Lars Buchhave (Buchhave et al. 2010).

Additional spectroscopic observations were obtained between July 17 and 2012 August 1 with the SOPHIE spectrograph (Perruchot et al. 2008; Bouchy et al. 2009, 2013) mounted on the 1.93 m telescope at Observatoire de Haute-Provence, France, using the High Efficiency mode (R ~ 39,000 at 550 nm) of the instrument. Spectra were extracted with the online standard pipeline.

Following a method similar to the Stellar Parameter Classification method (Buchhave et al. 2012), the atmospheric parameters of Kepler-76 were determined from the SOPHIE spectra by cross-correlating the observed spectral regions not affected by telluric lines against a library of synthetic spectra (Hauschildt et al. 1999), with varying values of effective temperature \( T_{\text{eff}} \), surface gravity \( \log g \), metallicity \( [m/H] \), and rotational velocity \( \nu \sin i \). For each of the observed spectra, we derived the best set of parameters that yielded the highest correlation. This was done by fitting a second-degree polynomial to the maximum correlation as a function of each parameter around the synthetic spectrum that yielded the best correlation. The final parameter values for a star were taken as the mean of the parameter values derived for each observed spectrum of that star, weighted proportionally to the inverse of the scatter of the maximum around the fitted polynomial.

The Phoenix library of synthetic spectra we used spans the following intervals in atmospheric parameters: 3000 K < \( T_{\text{eff}} \) < 10,000 K, \(-0.5 < \log g < 5.5 \) (cgs), and \(-1.5 < [m/H] < +0.5 \). The spacing in \( T_{\text{eff}} \) is 100 K for \( T_{\text{eff}} < 7000 \) K, and 200 K elsewhere. The spacing in \( \log g \) and \([m/H] \) is 0.5 dex. The interval and spacing of the \( \nu \sin i \) values in our algorithm are free parameters set by the user, since each synthetic spectrum chosen from the library is convolved with a rotational profile \( G(\nu) \) (e.g., Gray 2005, p. 465; Santerne et al. 2012) and a Gaussian representing the instrumental broadening of the line, just before calculating the cross-correlation function (CCF).

The cross-correlation was performed using TODMOR (Zucker & Mazeh 1994; Zucker et al. 2003, 2004)—a two-dimensional correlation algorithm, assuming the light contribution of the secondary is negligible. In TODMOR, the CCFs are calculated separately for each echelle order, and then combined to a single CCF according to the scheme proposed by Zucker et al. (2003). The atmospheric parameters found this way are listed in Table 2. The relatively large uncertainties result mainly from the addition of possible systematic errors (see, e.g., Bruntt et al. 2010, 2012; Torres et al. 2012).

The primary mass was estimated using the atmospheric parameters derived from the spectra and a grid of \( Y^2 \) stellar isochrones (Yi et al. 2001; Demarque et al. 2004). This was done by taking into account all age and mass values that fall into the ellipsoid in the \( (T_{\text{eff}}, \log g, [\text{Fe/H}]) \) space defined by the atmospheric parameters and their errors. To illustrate the process, Figure 4 shows two sets of \( Y^2 \) stellar isochrones of 0.2, 0.4, 1, 2, 4, 8, and 10 Gyr—one for \([\text{Fe/H}] = 0.05 \) (solid lines) and one for \([\text{Fe/H}] = -0.27 \) (dashed lines). The ellipse defined by the estimated \( T_{\text{eff}} \) and \( \log g \) and their uncertainties is also shown. A lower limit of 0.2 Gyr on the stellar age was set to ignore possible pre-main-sequence solutions. This procedure yielded a mass estimate of \( 1.20 \pm 0.09 \) \( M_\odot \). Following Basu et al. (2012), we have conservatively doubled the mass errors to take into account possible uncertainties in the stellar model parameters.

RVs were derived for the TRES observations in two different ways, as described in detail by Faigler et al. (2012). First, we derived absolute velocities using cross-correlations of the observed spectra against the template from our library of synthetic spectra that yielded the best match (with \( T_{\text{eff}} = 6000 \) K, \( \log g = 4.0 \) cgs, \( \nu \sin i = 12 \) km s\(^{-1}\), and solar metallicity). The absolute velocity analysis used just the spectral order containing the Mg\( \text{II} \) triplet and was calibrated using IAU RV standard stars. With the goal of achieving better precision, we also derived velocities

| \( T_{\text{eff}} \) (K) | \( \log g \) (dex) | \([m/H]\) (dex) | \( \nu \sin i \) (km s\(^{-1}\)) | \( M_\star \) (\( M_\odot \)) |
|-----------------|----------------|----------------|----------------|----------------|
| 6300 ± 200      | 4.2 ± 0.3      | -0.1 ± 0.2     | 6.5 ± 2        | 1.2 ± 0.2      |

Table 2

Atmospheric Parameters of Kepler-76
using about two dozen spectral orders, correlating the individual observations against a template based on the strongest exposure. Thus, the multi-order velocities are relative to the observation chosen as the template. They are reported in Table 3.

For the SOPHIE observations, RVs were derived by computing the weighted CCF of the spectra with a numerical spectral mask of a G2V star (Baranne et al. 1996; Pepe et al. 2002). For the last five exposures, which were contaminated by scattered moon light, we subtracted the sky using the fiber B spectrum (Santerne et al. 2009), before deriving the RVs. Table 3 lists the RV measurements and their uncertainties.

The first RV measurements of Kepler-76 showed variability consistent with the photometric orbital phase, so we continued observations in order to allow an orbital solution independent of the BEER analysis. The derived eccentricity of the solution was statistically indistinguishable from zero, so we reran the solution with eccentricity fixed to zero. Figure 5 shows the follow-up RV measurements and the velocity curve for the orbital solution, folded with the period found, and the top section of Table 4 lists the derived orbital elements for the independent RV solution. The center-of-mass velocities $\gamma_T$ and $\gamma_S$ for the independent RV sets from TRES and SOPHIE differ by 5.68 km s$^{-1}$. This is because the TRES velocities are relative to the strongest observation, while the SOPHIE velocities are meant to be on an absolute scale. If the absolute TRES velocities derived using the Mg b order are used instead of the relative velocities, then $\gamma_T = -5.18$ km s$^{-1}$, quite close to the SOPHIE value of $\gamma_S = -5.31$ km s$^{-1}$. For the joint analysis reported below, the two independent velocity sets were shifted to a common zero point using the $\gamma$ velocities reported in Table 4.

Next, in order to obtain a combined solution from photometry and RV measurements, we reran the RV model using the photometric period and ephemeris, with their uncertainties, as priors. The bottom section of Table 4 lists the orbital elements derived from this photometry-constrained RV solution, and the estimated minimum secondary mass, $M_p \sin i$.

![Figure 4](image1.png)

**Figure 4.** $Y^2$ stellar isochrones, from Demarque et al. (2004), of 0.2–10 Gyr for metallicities [Fe/H] = 0.05 (solid lines) and [Fe/H] = −0.27 (dashed lines). The estimated $T_{\text{eff}}$ and $\log g$ of Kepler-76 with their uncertainties are marked by a star and an ellipse. (A color version of this figure is available in the online journal.)

![Figure 5](image2.png)

**Figure 5.** RV measurements folded at the derived orbital period. In the top panel, the solid line represents the photometry-constrained orbital RV model and the horizontal-dashed line indicates the center-of-mass velocity. Circles denote SOPHIE RV points and squares denote TRES RV points. The residuals are plotted at the bottom panel. Note the different scales of the upper and lower panels. (A color version of this figure is available in the online journal.)

| Time (BJD−2456000) | RV (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | Instrument |
|---------------------|-----------------|---------------------|------------|
| 76.930366           | 0.581           | 0.069               | TRES       |
| 83.895818           | 0.161           | 0.110               | TRES       |
| 84.868623           | 0.546           | 0.072               | TRES       |
| 87.836880           | 0.607           | 0.103               | TRES       |
| 107.916759          | 0.586           | 0.098               | TRES       |
| 115.796005          | 0.727           | 0.114               | TRES       |
| 117.775394          | 0.100           | 0.082               | TRES       |
| 207.682884          | 0             | 0.069               | TRES       |
| 126.378842          | −4.999         | 0.036               | SOPHIE     |
| 128.75439           | −5.597         | 0.036               | SOPHIE     |
| 129.562543          | −5.081         | 0.036               | SOPHIE     |
| 130.416149          | −5.560         | 0.091               | SOPHIE     |
| 131.389038          | −5.341         | 0.061               | SOPHIE     |
| 137.536798          | −5.196         | 0.132               | SOPHIE     |
| 138.483304          | −5.194         | 0.057               | SOPHIE     |
| 139.470933          | −5.615         | 0.080               | SOPHIE     |
| 140.470516          | −4.992         | 0.114               | SOPHIE     |
| 141.450747          | −5.171         | 0.082               | SOPHIE     |
4. PHOTOMETRIC MODELING OF THE LIGHT CURVE

For a more complete photometric analysis of this transiting hot Jupiter we used the Kepler light curves of the Q2 to Q13 quarters, spanning 1104 days. First, we fitted the cleaned and detrended data with the BEER model while masking out data points in or around the transits and occultations. The fitted amplitudes, after correction for a third light using the KIC estimate, are listed in Table 6. We then subtracted the BEER model from the data and analyzed the data points in and around the transits and occultations. For that we ran a Markov chain Monte Carlo (MCMC) analysis, while fitting the transit data points using a long-cadence-integrated Mandel & Agol (2002) model combined with the best-fit Mandel & Agol (2002) model with quadratic limb darkening, assuming a circular orbit. The model limb darkening coefficients could not be constrained, so we kept them fixed at values interpolated from Claret & Bloemen (2011) using the stellar parameters derived from spectroscopy. We then fitted the occultation data keeping the geometric parameters derived from the transit fixed, and assuming a linear limb darkening coefficient of 0.5 for the planet, while looking for the occultation depth that best fits the data.

5. INFLATED BEAMING AMPLITUDE AND PLANET EQUATORIAL SUPERROTATING JET

The spectroscopic RV observations and the light curve transit and occultation analysis yielded independent orbital solutions with ephemeris and period nicely consistent with the BEER ephemeris and period. To compare the measured RV amplitude...
with the beaming-based predicted RV amplitude, one needs to evaluate the $\alpha_{\text{beam}}$ factor, which corrects for the Doppler shift of the stellar spectrum relative to the observed band of the telescope (Rybicki & Lightman 1979; Faigler & Mazeh 2011).

To estimate the $\alpha_{\text{beam}}$ value, we used spectra from the library of the Castelli & Kurucz (2004) models close to the estimated temperature, metallicity, and gravity of the primary star, numerically shifting them relative to the Kepler response function, while taking into account the photon counting nature of Kepler (Loeb & Gaudi 2003; Bloemen et al. 2011; Faigler et al. 2012). For clarity, we note that by definition $\alpha_{\text{beam}} = (3 - \alpha/4) = (\langle B \rangle/4)$, where $\alpha$ is the power-law index used by Loeb & Gaudi (2003) and $\langle B \rangle$ is the photon-weighted bandpass-integrated beaming factor used by Bloemen et al. (2011). The result of this calculation gave $\alpha_{\text{beam}} = 0.92 \pm 0.04$, resulting in an RV semi-amplitude of $K_{\text{beam}} = 1.11 \pm 0.17$ km s$^{-1}$. The RV semi-amplitude predicted from the beaming effect was 3.5 times larger than the measured amplitude, with a difference significance of about 4.5$\sigma$ between the two.

A possible explanation for this inflated photometric beaming amplitude might be a phase shift of the reflection signal, due to the superrotation phenomenon, which involves eastward advection of gas by an equatorial superrotating jet within the atmosphere of a corotating companion. Showman & Guillot (2002) predicted through a three-dimensional atmospheric circulation model that tidally locked, short-period planets develop a fast eastward, or superrotating, jet stream that extends from the equator to latitudes of typically 20°–60°. They showed that in some cases (depending on the imposed stellar heating and other factors) this jet causes an eastward displacement of the hottest regions by 10°–60° longitude from the substellar point, resulting in a phase shift of the thermal emission phase curve of the planet. This prediction was confirmed by Knutson et al. (2007, 2009) through Spitzer infrared observations of HD 189733, which indicated a phase shift of 16° ± 6° in the 8 $\mu$m band and 20°–30° in the 24 $\mu$m band.

In general, what we call a reflection modulation is actually the light scattered off the planet in combination with radiation absorbed and later thermally re-emitted at different wavelengths. The two processes are controlled by the Bond albedo, $0 < A_B < 1$, and the day–night heat redistribution efficiency, $0 < \epsilon < 1$, which can be constrained only if observations
of the phase modulation or the secondary eclipse are available in different wavelengths (Cowan & Agol 2011). This makes it impossible to distinguish between reflected and re-radiated photons from the single-band \textit{Kepler} light curve we have in hand. Cowan & Agol (2011) discuss HAT-P-7 as an example, and show that its \textit{Kepler} light curve can be explained as mostly reflected light at one limit, to mostly thermal emission at the other limit, with an entire range of models between them being consistent with the light curve. This is important for the current discussion, as we expect superrotation to shift only the thermal re-emission, while leaving the scattered light component unshifted.

To estimate the maximum fraction of the reflection amplitude originating from thermal re-emission in our case, we follow Cowan & Agol (2011) and estimate the no albedo, no redistribution, effective dayside temperature \( T_{\text{e}} = 2670 \) K, which translates in the \textit{Kepler} band to a maximum reflection amplitude \( A_{\text{ref}} \approx 37 \) ppm. This means that the measured amplitude of \( \approx 50 \) ppm can be explained mostly by thermal re-emission. The actual fraction of thermal emission in this case is probably smaller, but this calculation indicates that the fraction of thermal emission in the visual \textit{Kepler} light curve phase modulation may be significant, making it a worthy effort to look for a superrotation phase shift in the light curve.

We suggest here, that if such a phase shift is present in the \textit{Kepler} light curve, it will show up in our phase curve model mainly as an inflated beaming amplitude. To illustrate that, we consider a simple superrotation model consisting of a phase-shifted geometric reflection/emission combined with a beaming modulation,

\[
M_{\text{SR}} = -A_{\text{ref}} \cos(\phi + \delta_{\text{SR}}) + A_{\text{beam}} \sin \phi \\
= -A_{\text{ref}} \cos \delta_{\text{SR}} \cos \phi + (A_{\text{beam}} + A_{\text{ref}} \sin \delta_{\text{SR}}) \sin \phi,
\]

where \( A_{\text{ref}} \) is the reflection/emission semi-amplitude, \( A_{\text{beam}} \) is the beaming semi-amplitude, \( \phi \) is the orbital phase relative to mid-transit, and \( \delta_{\text{SR}} \) is the superrotation phase shift angle. This model suggests that if a phase shift is present \textit{and} the reflection amplitude is larger than, or of the order of, the beaming amplitude, then the underlined term in Equation (1) may add substantially to the amplitude of the \( \sin \phi \) modulation, mimicking an inflated beaming effect.

To test our conjecture that the beaming/ellipsoidal inconsistency is a result of a superrotation phase shift of the reflection/emission phase modulation, we fitted the data using the derived system parameters (Tables 2 and 5) and the BEER effects equations (Faigler & Mazeh 2011), while looking for the planetary mass, geometric albedo, and phase shift of the Lambertian phase function that minimized the \( \chi^2 \) of the fit. Adding the phase-shift parameter to the model resulted in a decrease of the \( \chi^2 \) value by 90, relative to the no-phase-shift model, indicating a substantially better agreement of the data with a model that combines beaming, ellipsoidal, and a phase-shifted Lambertian reflection. An \( F \)-test shows that fitting the data while allowing for a phase shift, as opposed to the no-phase-shift null model, yields a better fit with a confidence level better than 9\( \sigma \). Table 6 lists the amplitudes derived by the BEER analysis, the planetary mass derived directly from the beaming versus the ellipsoidal amplitudes, and the spectroscopic RV derived planetary mass.

The table then lists the planetary mass, phase-shift angle, and geometric albedo resulting from the superrotation model. The superrotation phase-shift estimate is small and well within the theoretical limit of 60° predicted by Showman & Guillot (2002). In addition, the derived planetary mass estimate is well within the 1\( \sigma \) range of the RV measured planetary mass, indicating that assuming superrotation resolves the inconsistency and provides a good estimate for the planetary mass, derived \textit{solely} from the \textit{Kepler} photometry, given a good stellar model.

### 6. DISCUSSION

This paper presents a new hot-Jupiter companion, Kepler-76b, initially identified by the BEER algorithm, and later confirmed by spectroscopic observations. The BEER detection was based on the photometrically measured amplitudes of the BEaming, Ellipsoidal, and Reflection effects, which were consistent with a planetary companion. This is just the third confirmed planet in the \textit{Kepler} field, after HAT-P-7b (Welsh et al. 2010) and TrES-2b (Barclay et al. 2012), for which its host light curve exhibits the three phase curve effects, and is the faintest of the three stars. It is also one of a few confirmed grazing exoplanets, showing a V-shaped transit and a partial occultation.
We have identified an inconsistency between the beaming amplitude and the spectroscopically measured RV. Similar inconsistencies between the planetary mass derived from the beaming amplitudes and the mass derived from the ellipsoidal amplitude were noticed previously by several authors for KOI-13 (Mazeh et al. 2012; Shporer et al. 2011) and TrES-2 (Barclay et al. 2012). We suggest here that these inconsistencies can be explained by a phase shift of the planetary thermal modulation due to the equatorial superrotation phenomena predicted by Showman & Guillot (2002) and later observed by Knutson et al. (2007, 2009) in the infrared for HD 189733. In such cases, we should be able to measure the superrotation phase-shift angle from the visual-band Kepler light curve of the system. As we do not expect scattered light to exhibit such a phase shift, visual band detection of the superrotation phase shift may yield a constraint on the ratio of scattered light to thermally re-emitted light from the planet.

Finally, we wish to briefly comment on the sensitivity of the BEER algorithm. The detection presented here exhibits the lowest-mass companion identified so far by the algorithm, indicating its possible current detection limit. As we require that a BEER candidate must show statistically significant beaming and ellipsoidal effects to be considered valid, we choose here the minimum of the semi-amplitudes of the two effects as the BEER detectability parameter of a planet. To estimate our ability to detect more planets and brown dwarfs, Figure 7 presents the calculated value of this parameter, using the Faigler & Mazeh (2011) equations, for known exoplanets of mass higher than 0.5 \( M_{\text{Jup}} \) and period shorter than 30 days, as of 2013 January (http://exoplanet.eu/), together with the measured value for Kepler-76b. The figure shows that there are six transiting and one RV detected planets with calculated amplitudes higher than that of Kepler-76b, suggesting that these systems could have been detected by the BEER algorithm, if their stellar and instrumental noise were similar to that of Kepler-76. It is also apparent that further enhancement of the algorithm sensitivity could significantly increase the number of potentially detectable planets. Given the fact that BEER can detect similar non-transiting objects, we expect to find more objects once we improve our detection threshold.

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**Facilities:** FLWO:1.5m(TRES), OHP:1.93m(SOPHIE)

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