A massive exoplanet candidate around KOI-13: independent confirmation by ellipsoidal variations

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ABSTRACT

We present an analysis of the KOI-13.01 candidate exoplanet system included in the 2011 September Kepler data release. The host star is a known and relatively bright ($m_{KP} = 9.95$) visual binary with a separation significantly smaller (0.8 arcsec) than the size of a Kepler pixel (4 arcsec pixel$^{-1}$). The Kepler light curve shows both primary and secondary eclipses, as well as significant out-of-eclipse light-curve variations. We confirm that the transit occurs round the brighter of the two stars. We model the relative contributions from (i) thermal emission from the companion, (ii) planetary reflected light, (iii) Doppler beaming and (iv) ellipsoidal variations in the host star arising from the tidal distortion of the host star by its companion. Our analysis, based on the light curve alone, enables us to constrain the mass of the KOI-13.01 companion to be $M_C = 8.3 \pm 1.25 M_J$ and thus demonstrates that the transiting companion is a planet (rather than a brown dwarf which was recently proposed by Szabo). The high temperature of the host star (spectral type A5-7V, $T_{eff} = 8511$–8020 K), combined with the proximity of its companion KOI-13.01, may make it one of the hottest exoplanets known, with a detectable thermal contribution to the light curve even in the Kepler optical passband. However, the single passband of the Kepler light curve does not enable us to unambiguously distinguish between the thermal and reflected components of the planetary emission. Infrared observations may help to break the degeneracy, while radial-velocity follow-up with $\sigma \sim 100$ m s$^{-1}$ precision should confirm the mass of the planet.

Key words: techniques: photometric – planets and satellites: detection – planets and satellites: fundamental parameters.

1 INTRODUCTION

In Mislis et al. (2011) we demonstrated the potential for estimating planetary masses solely from light-curve (LC) data for a restricted sample of systems. The distinguishing characteristic of these systems is that the planet must be both massive enough and close enough to the host star to induce significant tidal distortions in the stellar ellipsoid. Such non-sphericity in the plane of the sky for a rotating star will lead to a periodic photometric signal which is detectable given sufficient signal-to-noise ratio. In Mislis et al. (2011) we applied the technique to the transiting exoplanet HAT-P-7 observed with Kepler, and estimated the mass of the planet to be $M_Planet(LC) = 1.27 \pm 0.12 M_J$ which is very close to the radial velocity (RV) solution, $M_Planet(RV) = 1.20 \pm 0.05$ (Welsh et al. 2010).

The second exoplanet candidate list released by the Kepler team in 2011 February, and published in Borucki et al. (2011), contains 1235 exoplanet candidates. The light curves span measurements taken between 2009 May and 2011 September. Motivated by our previous work, we searched the light curves of all 1235 planetary candidates for evidence of ellipsoidal variation. The brightest and best candidate for a star showing strong out-of-eclipse ellipsoidal variations is KOI-13.01$^1$ candidate, which is identified with an A5-7V type star (with a close companion 0.8 arcsec to the west$^2$).

The LC magnitude is $m_{KP} = 9.95$ (Kepler passband), and shows primary and secondary eclipses with a published period of 1.763 5892 d. The shape of the eclipses is indicative of either a small transiting companion or a blended system, whereby a deeper eclipse is diluted by contaminating light from nearby stars in the same Kepler pixels.

KOI-13.01 is already the subject of a thorough analysis of the source characteristics and the transit shape by Szabo et al. (2011). They conclude that the system comprises a double A-star wide binary system, the more massive component of which is being eclipsed by a brown dwarf or very low mass star on the basis of a radius determination $R_C = 2.2 \pm 0.3 R_J (R_J: companion radius)$. In this paper we independently confirm that the brighter component of

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$^1$ Shortly before submission of this manuscript we became aware of an analysis of the same system, drawing similar conclusions, submitted by Mazeh et al. (2011).

$^2$ Szabo et al. (2011).
the visual binary is the host star for the eclipses (Section 2). Barnes et al. (2011) use a more sophisticated analysis to measure the radius of the host star and transiting companion, including the effects of a gravity-darkened rapidly rotating host star. The updated values ($R_C = 1.4 \pm 0.016 R_\star$, $R_A = 1.77 \pm 0.014 R_\odot$) are significantly smaller than those found by Szabo et al. 2011, and lead Barnes et al. (2011) to conclude that KOI-13.01 may be a planet. Finally, Rowe et al. (2011) presented the system at the 2011 AAS meeting and also suggested that the companion is a planet.

In Section 3 we perform modelling of the out-of-eclipse photometric variation, which puts very strong constraints on the mass of the eclipsing/transiting companion, and lends support to the argument that KOI-13.01 has a planetary mass.

## 2 Kepler DATA

We have used the *Kepler* public light curve and centroid curve data available from the *Kepler* archive hosted by the Multimission Archive at STScI (MAST)

http://archive.stsci.edu

for our analysis. The observations comprised four long-cadence and four short-cadence data sets (spanning *Kepler* Q1–Q3). The data were processed by the Pre-Search Data Conditioning (PDC) module (Kepler Data Processing Handbook).

For objects brighter than $m_{KP} = 11.3$ some saturation, and then bleeding, of the CCD pixels will occur. This charge is not lost, and using an appropriately shaped mask will preserve the flux, and maintain precise photometry even for extremely bright sources (Gilliland et al. 2010, 2011). Both short-cadence and long-cadence data are equally affected given that they use the same 6-s exposure. In Fig. 1 we show the *Kepler* light curve folded on the period of 1.763 5892 d found by Borucki et al. (2011), with phase zero set to be the centre of the primary minimum.

### 2.1 Identification of the companion host star

Borucki et al. (2011) suggest that the source associated with KOI-13 is actually a double star (separation 0.8 arcsec, $\Delta$mag = 0.4). Szabo et al. (2011) show that the *Kepler* source is coincident with the double star (BD+46 2629A and B, hereafter KOI-13A and KOI-13B), two stars of spectral class A, separated by 1.18 $\pm$ 0.02 arcsec with a magnitude difference of $\Delta$mag = 0.20 $\pm$ 0.04 mag.

### 2.2 Removal of the blended light

For our analysis, the Q1, Q2 and Q3 data sets were used, corresponding to a light curve spanning 418 d in total. The light curve was first corrected to remove the flux from the secondary which we assume to be constant. A magnitude difference of $\Delta$mag = 0.2 was used, and 45 per cent of the total flux is subtracted from the *Kepler* light curve (Szabo 2011).

The light curve was phase folded on the best-fitting *Kepler* period of $P = 1.763$ 5892 (Borucki et al. 2011), rebinned by a factor of 1770, and phase = 0 set to be the mid-point of the primary transit. We use the updated values for $R_C$, $R_A$, $\alpha$ (semimajor axis of the orbit) and inclination ($i$) from Barnes et al. (2011) ($R_C = 1.76 \pm 0.014 R_\odot$, $R_A = 1.4 \pm 0.014 R_\odot$, $\alpha = 0.0367$ au and $i = 85.9$). The phase-folded light curve, including the secondary eclipse but excluding the primary transit to emphasize the out-of-eclipse variation, is shown in Fig. 1. Finally we found no evidence for additional periods in the *Kepler*-corrected light curve, such as Mazeh et al. (2011) suggested ($P = 1.0595$ d).

## 3 MODELLING

In our modelling, we consider four main components which contribute to the out-of-eclipse phase dependence of the light curve of KOI-13, summarized in the following equation:

\[
\frac{f_{\text{tot}}}{f_{\star}} = 1 + f_{\text{b,day}} + f_{\text{b,night}} + f_{\text{ref}} + f_{\text{ell}} + f_{\text{lop}}
\]

(1)

In our simple model we include (1) thermal emission from the companion (day and night side – $f_{\text{b,day}}$, $f_{\text{b,night}}$), (2) reflected light

Howell et al. (2011) use speckle imaging to find a separation of 1.16 arcsec and $\Delta$mag = 0.85 at 562 nm ($\Delta$mag = 1.03 at 692 nm) between the two components. However, this photometric difference between the two stars is in serious disagreement with the Szabo et al. (2011) photometry. Having inspected the Szabo et al. (2011) image, we have opted to adopt their value for the magnitude difference between the two stars in the *Kepler* bandpass (as do Barnes et al. 2011). We note that this is a V-band measurement, which is not identical to the *Kepler* passband, but for an A-type star, the differences are small. In our analysis (Section 5) we consider the effects of changing the contribution of this companion star to the *Kepler* light curve. Based on an unresolved spectrum, and a combination of resolved and unresolved photometry, Szabo et al. use model isochrones to find effective temperatures for the A and B components of $T_{\text{eff}}^A = 8511$ K (8128–8913 K) and $T_{\text{eff}}^B = 8222$ K (7852–8610 K), respectively.

The centroid curves for KOI-13 are shown in the middle panel of Fig. 2. Batalha et al. (2010) have demonstrated that the very tiny shifts in centroid, expected for blended occulting sources, can be measured accurately from the *Kepler* data. Thus, they can be used to show where the largest variations in flux are occurring with respect to the centre of light. The strong periodic offset in the *Kepler* centroid curve data agrees extremely well with the time of primary transit. Fig. 2 (bottom) also shows an illustration of the direction (and magnified amplitude) of the source centroid during primary eclipse. This can be explained simply, if KOI-13A becomes fainter during every transit and the centre of light moves towards the west (towards KOI-13B). This interpretation independently confirms the conclusions from Szabo et al. (2011) who used both the *Kepler* pixel light curves and additional ground-based lucky imaging. Thus we confirm that KOI-13A is the host to the companion.
D. Mislis and S. Hodgkin can solve for the mass of the companion:
\[ \frac{f_{\text{th}}(\theta)}{f_*} = A(\theta) \left( \frac{R_C}{R_*} \right)^2 \cdot \text{Const}, \]  
\[ \frac{f_{\text{ref}}(\theta)}{f_*} = \Phi(\theta) \left( \frac{R_C}{\alpha} \right)^2 \cdot a_{\text{eff}}, \]  
\[ \frac{f_{\text{ell}}(\theta)}{f_*} = \beta \frac{M_C}{M_*} \left( \frac{R_*}{\alpha} \right)^3 \sin^2(t), \]  
\[ \frac{f_{\text{day}}(\theta)}{f_*} = (3 - \rho) \frac{K}{c}, \]  
where \( f_{\text{th}}/f_* \) is the relative flux from the thermal emission [for the day side, \( f_{\text{th, day}}/f_* \), \( A(\theta) = \Phi(\theta) \)] and for the night side, \( f_{\text{th, night}}/f_* \), \( A(\theta) = 1 - \Phi(\theta) \)], \( f_{\text{ref}}/f_* \), is the relative flux from the reflected light, \( f_{\text{ell}}/f_* \), is the relative flux from the ellipsoidal variations and \( f_{\text{day}}/f_* \), is the Doppler boosting relative flux. \( \Phi(\theta) \) is the phase function, \( \alpha \) is the semimajor axis, \( \text{Const}(T_{\text{eff}}, \lambda, a_{\text{bol}}, \epsilon) \) is a constant function of the effective temperature of the star and the temperature of the planet (Mislis et al. 2011), and \( \beta \) is the gravity darkening. Finally, \( K \) is the radial-velocity amplitude and \( \rho \) is a function of \( \rho(\lambda, T_{\text{eff}}) \) :
\[ \rho = \frac{e^{hc/\lambda T_{\text{eff}}} (3 - hC/\lambda T_{\text{eff}}) - 3}{e^{hc/\lambda T_{\text{eff}}} - 1}. \]

Our model for the flux changes arising from the ellipsoidal distortion (equation 4) is a simple approximation, and assumes that the system is in tidal equilibrium (Rowe et al. 2010; Carter, Rappaport & Fabrycky 2011; Mislis et al. 2011). The \( a_{\text{bol}} \) and \( \epsilon \) parameters refer to the bolometric albedo and the energy circulation, respectively. Both equations (2) and (3) are a function of \( \Phi(\theta) \), but the mass of the secondary body is a dependent parameter only in equations (4) and (5). We note that in our equations the terms \( R_*/\alpha \) and \( R_C/\alpha \) both appear. These are measured directly from the depth and duration of the primary transit and the period of the system. For consistency these values are taken from Barnes et al. (2011).

If we were to solve for and remove the first two components (thermal emission and reflected light), the residual light curve will contain the mass information (Fig. 3 – bottom). An important result of the model is that the ellipsoidal component contributes zero to the total LC flux (assuming \( \epsilon = 0 \) at phase 0.5 (centre of the secondary eclipse), and that the phase function depends only very slightly on the balance between the day- and night-side properties of any companion’s emission (i.e. it is extremely difficult to measure this with single passband optical data). Thus the thermal emission and the reflected light components will be very difficult to distinguish in a single filter. Nevertheless, one of the goals of modelling the full *Kepler* light curve for KOI-13 is to try to constrain the brightness temperature of KOI-13.01. The main differences between our model and other algorithms (such as BEER – Faigler & Mazeh 2011) are that (i) we investigate two phase functions (Lambert and geometrical spheres – Mislis et al. 2011) and (ii) we include distinct reflected and thermal components (including day and night side, \( a_{\text{bol}} \), \( \epsilon \)). The choice of phase functions can alter the mass of the planet by 36 percent (see Section 5).

KOI-13A is so hot (\( T_{\text{eff}} = 8511 \pm 400 \) K), and the candidate planet so close (\( \alpha = 0.0367 \) au, \( \sim 4.5 R_* \)), that the thermal flux of the candidate is likely to be non-negligible, even at optical wavelengths. The equilibrium temperature for any zero-albedo companion to KOI-13.01 is \( T_{\text{eq}} = T_{\text{eff}} \sqrt{R_C/2\pi} = 2864 \) K (for \( R_* = 1.694 \pm 0.013 R_\odot \); Barnes et al. 2011), assuming that it does not have its own internal source of heating (as one would expect for a brown dwarf).
The hottest known planet discovered to date is probably WASP-33b, with an equilibrium temperature of \(2750\,\text{K}\), and a brightness temperature of \(T_b = 3620^{+200}_{-220}\,\text{K}\) (Smith et al. 2011), measured from ground-based infrared (\(\lambda = 0.9\,\mu\text{m}\)) observations of the secondary eclipse (depth of 0.109 per cent). The relative thermal emission for WASP-33b in the optical (Kepler passband) would be \(10^{-4} \times f_\odot\) (assuming a blackbody). We note that the secondary eclipse of KOI-13.01 is \(1.2 \times 10^{-5} f_\odot\) (Szabo et al. 2011) in the Kepler passband.

As a starting point, we consider three simple scenarios for the phase LC data alone, i.e. excluding all data points within the primary transit or the secondary eclipse. In the case of \(C_{\text{therm}}\) we assume that the bolometric albedo of the companion is fixed at \(a_{\text{bol}} = 1.0\), which means that the planet is perfectly reflective, that the thermal emission of the planet is zero, and therefore the model contains only reflected light and ellipsoidal variations. In the case of \(C_{\text{ell}}\), we assume that the geometric albedo is zero (\(a_g = 0.0\)), so the reflected light is zero and the model contains only thermal emission ellipsoidal variations, and Doppler boosting \([f_{\text{iso}} = \text{a function of } \rho(\lambda, T_{\text{eff}}) \text{ and } K \text{ – equation 6}]\). Finally, in the case of \(C_{\text{hybr}}\) we consider a hybrid case, and allow \(a_g\) and \(a_{\text{bol}}\) to be free parameters, i.e. both thermal emission and reflected light are present in the light curve in addition to any ellipsoidal variations. So in \(C_{\text{ell}}\) we fit for \(a_g\) and \(M_C\), in \(C_{\text{therm}}\) we fit \(a_{\text{bol}}\), \(\epsilon\) (energy circulation) and \(M_C\), and in \(C_{\text{hybr}}\) we fit all the parameters above. Eccentricity \(e\) and the periastron angle \(\omega\) are free parameters in all three scenarios.

As a final step, we add the primary transit and secondary eclipse data back into the light curve, and re-assess \(C_{\text{hybr}}\) (and name it \(C_{\text{hybr}}\)), primarily to see if the additional information on the depth of the secondary eclipse can provide useful constraints on the thermal emission from the planet (as has been suggested by Mazeh et al. 2011).

An important and unresolved factor is how we treat the phase function of the reflected light. We consider two approaches: (1) modelling the planet as a Lambert sphere (Russell 1916), assuming that the intensity of the reflected light is \(f_{\text{ref}} = 1/\pi\) at phase \(z = \pi/2\) (as in the case of Venus); (2) an alternative choice would be to assume that the reflected light is \(f_{\text{ref}} = 0.5\) at phase \(z = \pi/2\). In Mislis et al. (2011) we demonstrate that this choice leads to a significantly different phase contribution for the reflected light, and therefore has a significant impact on the derived mass of the companion. The companion mass is significantly larger (by 36 per cent) if we use the Lambert sphere compared to the geometrical sphere. In our analysis we are unable to distinguish between the two cases. Thus, in the next section we present the results from the Lambert sphere case, which gives the larger companion mass.

### 4 RESULTS

With all three cases we find that the orbit is circular and that the eccentricity value is \(e = 0.0 \pm 0.05\). All three scenarios require strong ellipsoidal variations to explain the phase light curve. The hybrid model \(C_{\text{hybr}}\) is significantly preferred with a confidence of 99 per cent (2.55\(\sigma\)) compared to \(C_{\text{therm}}\), and 99.6 per cent (2.85\(\sigma\)) compared to \(C_{\text{ell}}\). Scenarios \(C_{\text{therm}}\) and \(C_{\text{ell}}\) are indistinguishable at the 1\(\sigma\) level. Table 1 shows the results of all three cases (excluding primary transit and secondary eclipse) and Fig. 3 (top) shows the Kepler light curve and the components for the \(C_{\text{hybr}}\) scenario. In all three cases, we agree on the mass of the unseen companion to within a few per cent, suggesting that the technique is largely independent of the precise nature (be it thermal or reflected) of the emission arising from the companion. Although note that the mass constraint improves as the model becomes more complex. Both \(C_{\text{therm}}\) and \(C_{\text{ell}}\) are significantly less good than the hybrid model, suggesting that components of both thermal and reflected light are contributing to the phase light curve. Note that we do not give errors on \(e\), \(a_{\text{bol}}\), and \(a_g\) in \(C_{\text{hybr}}\) because they are essentially unconstrained at the 1\(\sigma\) level, with large degeneracies between \(a_g\), \(a_{\text{bol}}\), and \(\epsilon\).

#### Table 1. Model results for the three main scenarios discussed in the text.

| Fitting Parameters | \(C_{\text{ell}}\) (reflected) | \(C_{\text{therm}}\) (thermal) | \(C_{\text{hybr}}\) (mixed) |
|--------------------|-----------------------------|-----------------------------|-----------------------------|
| \(M_C\) (\(M_\odot\)) | \(8.0 \pm 1.1\) | \(8.3 \pm 1.0\) | \(8.3 \pm 0.9\) |
| \(\epsilon\) | 0.17\(\pm 0.17\) | 0.10 | 0.10 |
| \(a_{\text{bol}}\) | 0.01\(\pm 0.01\) | 0.80 | 0.80 |
| \(a_g\) | 0.28\(\pm 0.1\) | 0.28\(\pm 0.28\) | 0.28\(\pm 0.28\) |
| \(\epsilon\) (\(\degree\)) | 0.0 \(\pm 0.05\) | 0.0 \(\pm 0.05\) | 0.0 \(\pm 0.05\) |
| \(\chi^2\) | 1.042 | 1.032 | 1.03 |
The mass derived from the best-fitting model of the candidate is $M_C = 8.3 \pm 0.9 M_J$, rather more massive than a typical hot Jupiter, but significantly below the brown dwarf or M dwarf mass proposed by Szabo et al. (2011). This error on $M_C$ is the error from fitting the model, and does not allow for the uncertainty in the mass of the primary, rather this should be seen as a 20 per cent error on the mass ratio, $M_C/M_* = 0.0039$. We take the mass from Szabo et al. (2011) to be $2.05 M_\odot$ and assume an error of 10 per cent. We also consider a 0.1 per cent error in the radius ratio $R_C/R_*$ (Barnes et al. 2011). Accounting for both of these leads to a final constraint on the mass of KOI-13.01, $M_C = 8.3 \pm 1.25 M_J$.

4.1 How hot is KOI-13.01?

Any attempt to constrain the brightness temperature of the companion is severely hampered by the problem of distinguishing between the reflected and thermal components of our model, exacerbated by the single passband. In principle, if there were no reflected light, nor ellipsoidal variations, we could use the difference between the depth of the secondary eclipse (star only) and the point just before ingress to (or after egress from) the primary transit (i.e. star plus planet night side) for an orbit with zero eccentricity (e.g. TrES-2; O’Donovan et al. 2010). In practice, this is rather more complicated, because very small contributions from the ellipsoidal variations, and the marginally visible reflected light components, are contributing to the total light of the system in phase. Moreover, they need to be included in the modelling to constrain the night-side contribution to the system flux. Mazeh et al. (2011) have ignored these effects, and estimate the temperature of the companion to be 2600 K. Our rather more complete treatment of the light curve includes both thermal and reflected components, and includes the secondary eclipse in a self-consistent manner.

This then is our motivation for scenario $C_{hyb}$ introduced in the previous section. We added back into the light curve an additional 36 (in eclipse) data points, while adding no additional parameters to the model, i.e. the shape of the secondary eclipse is completely described by $C_{hyb}$. A little surprisingly, the additional data do nothing to improve our constraints on the nature of the secondary as parametrized by $e_q$, $a_{eq}$ and $e$. Perhaps this should not be so surprising, the depth of the secondary eclipse in a single filter is unlikely to tell us very much about the ratio of thermal to reflected emission from the planet’s atmosphere. Infrared measurements could perhaps make a significant impact here, as they could be combined with the optical passband to shed light on the colour of the planet. We also note that our solution to the mass of KOI-13.01 is not affected by the additional data points (see Fig. 4).

5 DISCUSSION

The very small amplitude of the ellipsoidal variations ($\sim 7.2 \times 10^{-5}$) for this period can only be explained by a body of planetary mass. Increasing the mass of the companion would significantly affect the depth of the secondary eclipse (star only) and the point just before ingress to (or after egress from) the primary transit (i.e. star plus planet night side) for an orbit with zero eccentricity (e.g. TrES-2; O’Donovan et al. 2010). In practice, this is rather more complicated, because very small contributions from the ellipsoidal variations, and the marginally visible reflected light components, are contributing to the total light of the system in phase. Moreover, they need to be included in the modelling to constrain the night-side contribution to the system flux. Mazeh et al. (2011) have ignored these effects, and estimate the temperature of the companion to be 2600 K. Our rather more complete treatment of the light curve includes both thermal and reflected components, and includes the secondary eclipse in a self-consistent manner.

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5 DISCUSSION

The very small amplitude of the ellipsoidal variations ($\sim 7.2 \times 10^{-5}$) for this period can only be explained by a body of planetary mass. Increasing the mass of the companion would significantly affect the depth of the secondary eclipse (Fig. 3 – bottom); therefore, we are confident that the mass of the companion KOI-13.01 is $8.3 \pm 1.25 M_J$ (i.e. a 1σ upper limit of 9.55$M_J$), assuming that there are no other contributions to the Kepler light curve that have so far been ignored in our analysis. It is worth noting that the ellipsoidal component of the light curve is visibly non-symmetric about phase 0.5 due to Doppler beaming (Fig. 3). The difference in heights is $\sim 4.3 \times 10^{-5}$, i.e. 3 per cent of the total phase function signal (assuming a simple model which neglects reddening). The mass we derive for the unseen companion to KOI-13A places the object below the minimum mass for deuterium burning (Spiegel, Burrows & Milson 2011).

One possible source of error in our estimation of the companion’s mass is the uncertainty in the contribution of the companion A star to the total Kepler light curve. If we increase the contribution from the nearby stellar component, and the flux we attribute to KOI-13A itself decreases, the mass of the planet becomes correspondingly larger, as the relative contribution of the ellipsoidal variations goes up. However, the effect is rather small when compared to our other sources of error. Specifically, a factor of $\pm 0.2$ mag leads to a change in the mass of $\pm 0.05 M_J$ for the companion. If the Howell et al. (2011) delta-magnitude is used, then the mass of KOI-13b will decrease by $\sim 20$ per cent; this implies that the body is even more planet-like.

Another possible source of error in our treatment of the system is our assumption that the companion behaves as a Lambert sphere. If the correct phase function should be represented by a geometrical sphere, then the best-fitting mass of the system will actually be significantly reduced by a systematic factor of 36 per cent, down to $M_C = 5.3 M_J$. See Mislis et al. (2011) for a more thorough discussion of this issue. For this paper, we are using the Lambert sphere phase function, which gives the maximum $M_C$.

The only real way to increase the mass of the unseen companion into the brown dwarf or stellar regime is to add yet another unresolved (in the Szabo et al. 2011 lucky imaging), and comparably bright, companion to the Kepler light curve. This seems unlikely, given that the spectral analysis of Szabo et al. (2011) is consistent with the photometry and the model isochrones. Ultimately, the mass of KOI-13.01 can only be fully determined with high spatial resolution (to resolve the components A and B), time-resolved spectroscopy. We estimate that the radial-velocity amplitude for the KOI-13A system will be $K \sim 870$ m s$^{-1}$ for our best-fitting mass. Although measuring precise radial velocities for a rapidly rotating and spatially blended A star is not simple, the formula in Battaglia et al. (2008) suggests that it should be eminently achievable, even with a small telescope, given sufficient signal-to-noise ratio. Ignoring the complications arising from disentangling the two spectra, we find that a signal-to-noise ratio of 10 000 per resolution element should enable us to reach a velocity precision of around 100 m s$^{-1}$.

The low amplitude of the ellipsoidal variations rules out the suggestion from Szabo (2011) that the companion could be an M star (Fig. 3). Therefore, KOI-13.01 is an exoplanet, and it is now illustrative to consider the object in the light of other exoplanets,
This mass value is versus $\sim R_8.3$ Kepler light curve, confirming $T_0.0 \pm T_0.05). Our results suggest that the density $\propto 9.2 M \propto$ based solely on the Doppler beaming $\propto R_1.1 = M R_T = \gamma = 3 R_T^2$ 2012 RAS $T M = 1.4)$ relation, and we note that planets found on exoplanet.org. KOI-13.01 is $\propto 422, i_\gamma \pm 3$. on 30 July 2018

Figure 5. $T_{eq}$ versus $R_C$ for planets found on exoplanet.org. KOI-13.01 is in the middle right-hand part of the plot. The solid line is the $R_C \propto T_{eq}^{1.4}$ model from Laughlin et al. (2011). For the plot we have used exoplanets.org (http://exoplanets.org/).

especially perhaps WASP-33b which also orbits an A star. In the $T_{eq}$ versus $R_C$ diagram (Fig. 5), we see that the current radius (Barnes et al. 2011) is in good agreement with the $T_{eq}$. Laughlin, Crismani & Adams (2011) examine the radius anomaly of exoplanets around their best-fitting $R \propto T_{eq}^\gamma$ (with $\gamma = 1.4$) relation, and we note that KOI-13.01, as a candidate for one of the hottest planets known, may provide a useful constraint on our understanding of planetary structures and atmospheres.

Mazeh et al. (2011) find a mass of $4 \pm 2$ and $6 \pm 3$ $M_1$ based on ellipsoidal variations and Doppler beaming effect using $R_C, R_e$ from Szabo et al. (2011). These values have since been updated by Barnes et al. (2011). In our analysis we found that the companion is significantly heavier, smaller and closer to the star than the Mazeh et al. (2011) measurement. Also, Shporer et al. (2011) found $M_e \sin(i) = 9.2 \pm 1.1 M_1$ based solely on the Doppler beaming effect (also using the Szabo et al. 2011 mass). The Doppler beaming signature in the light curve is roughly an order of magnitude smaller than the ellipsoidal variation, as Shporer et al. (2011) show in their paper. Assuming an inclination of $i = 85.9$, the planetary mass from Shporer et al. is $8.1 \leq M_e \leq 10.3$. This mass value is significantly heavier than the Mazeh et al. value (both teams use the same algorithm and the same system parameters), but agrees with our mass value.

6 CONCLUSIONS

We present modelling of the KOI-13.01 Kepler light curve, confirming the planetary nature of the companion. Our analysis illustrates the wealth of information that can be extracted from high-precision light curves, in the absence of spectroscopy. We find that the out-of-eclipse light curve of KOI-13.01 is dominated by two effects. The light contributed by the planet is at the same amplitude as the ellipsoidal variations induced in the star.

We are unable to solve for the relative contributions of thermal and reflected emission from the planet; however, we expect the planet to be one of the hottest known, given its close proximity to an A star, and its large radius. The equilibrium temperature for any zero-albedo companion to KOI-13.01 is $T_{eq} = T_{eff} \sqrt{R_C/2 \alpha} = 2864$ K, which is rather hotter than calculated for WASP-33b and WASP-12b. We suggest that infrared observations would help to disentangle the thermal and reflected components of the light curve.

By modelling the light curve, we find that the mass of the planet is $M_e = 8.3 \pm 1.25 M_J$, robust against any assumptions about the albedo of the planet. We also find that the planet is orbiting in a circular orbit ($e = 0.0 \pm 0.05$). Our results suggest that the density of the planet is around three times larger than Jupiter’s density. This value is not surprising. There are much more dense exoplanets, such as XO-3b (density $\sim 6.5$ times that of Jupiter – exoplanet.org).

We have studied the case that the system is an M dwarf or brown dwarf eclipsing companion, but neither of these solutions can explain the light curve we observe. The expected radial-velocity amplitude for KOI-13 system is $K \sim 870$ m s$^{-1}$, which will be relatively easy to measure despite the nature of the primary (a rapidly rotating A star) and the contamination from the close A-star companion. It would be an interesting exercise to search all of the Kepler light curves to look for the signature of ellipsoidal variations as a planet detection method, even in the absence of transits.

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REFERENCES

A massive exoplanet candidate around KOI-13

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