Detection of visible light from the darkest world

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ABSTRACT
We present the detection of visible light from the planet TrES-2b, the darkest exoplanet currently known. By analysis of the orbital photometry from publicly available Kepler data (0.4–0.9 μm), we determine a day–night contrast amplitude of 6.5 ± 1.9 ppm (parts per million), constituting the lowest amplitude orbital phase variation discovered. The signal is detected to 3.7σ confidence and persists in six different methods of modelling the data and thus appears robust. In contrast, we are unable to detect ellipsoidal variations or beaming effects, but we do provide confidence intervals for these terms. If the day–night contrast is interpreted as being due to scattering, it corresponds to a geometric albedo of Aₔ = 0.0253 ± 0.0072. However, our models indicate that there is a significant emission component to dayside brightness, and the true albedo is even lower (<1 per cent). By combining our measurement with Spitzer and ground-based data, we show that a model with moderate redistribution (Pₙ ≥ 0.3) and moderate extra optical opacity (κ' ≃ 0.3–0.4) provide a compatible explanation to the data.

Key words: techniques: photometric – stars: individual: TrES-2.

1 INTRODUCTION
Orbital photometric phase variations have long been used in the study and characterization of eclipsing binaries (Wilson 1994), where the large masses and small orbital radii result in phase variations at the magnitude to millimagnitude level. The three dominant components of these variations are (i) ellipsoidal variations due to the non-spherical nature of a star caused by gravitational distortion (e.g. Welsh et al. 2010), (ii) relativistic beaming due to the radial motion of the star shifting the stellar spectrum (e.g. Maxted, Marsh & North 2000) and (iii) reflected/emitted light, which varies depending on what phase of a body is visible (e.g. For et al. 2010). The visible bandpass orbital phase variations of a star due to a hot-Jupiter companion are much smaller – around the parts-per-million (ppm) level – and thus have eluded detection until relatively recently. The high-precision space-based photometry of CoRoT (0.56–0.71 μm) (Baglin et al. 2009) and Kepler (Basri, Borucki & Koch 2005) have opened up this exciting new way of studying exoplanets for the first time, with several detections recently reported in the literature.

(i) CoRoT-1b (Snellen, de Mooij & Albrecht 2009): reflected/emitted light amplitude 126 ± 36 ppm.
(ii) HAT-P-7b (Welsh et al. 2010): ellipsoidal amplitude 37 ppm, reflected/emitted light amplitude 63.7 ppm.
(iii) CoRoT-3b (Mazeh & Faigler 2010): ellipsoidal amplitude (59 ± 9) ppm, beaming amplitude (27 ± 9) ppm.
(iv) Kepler-7b (Demory et al. 2011): reflected/emitted light amplitude (42 ± 4) ppm.

In this Letter, we investigate the hot-Jupiter orbiting the G0V star TrES-2 (O’Donovan et al. 2006), where we detect a reflected/emitted light amplitude of (6.5 ± 1.9) ppm to a confidence of 3.7σ or 99.98 per cent. We also measure the ellipsoidal variation and relativistic beaming amplitudes to be (1.5 ± 0.9) and (0.2 ± 0.9) ppm, respectively, which are broadly consistent with theoretical expectation.

If our detected signal is interpreted as being purely due to scattering, then the corresponding geometric albedo would be Aₔ = 0.0253 ± 0.0072 [using system parameters from table 2, column 2 of Kipping & Bakos 2011, hereinafter (KB11), as will be done throughout this work], meaning that just four months of Kepler’s exquisite photometry has detected light from the darkest exoplanet yet found. Extrapolating to a 6-year baseline, one can expect to detect albedos ≥0.1 (to 3σ confidence) at similar orbital radii down to Rₚ ≃ 3.0 Rₛ. This clearly highlights the extraordinary potential which would be granted by an extended mission for Kepler.

2 OBSERVATIONS AND ANALYSIS

2.1 Data acquisition
We make use of ‘Data Release 3’ (DR3) from the Kepler mission, which consists of quarters 0, 1 and 2 (Q0, Q1 and Q2). Full details...
on the data processing pipeline can be found in the DR3 handbook. The data include the use of Barycentric Julian Date (BJD) time stamps for each flux measurement, which is crucial for time-sensitive measurements. All data used are publicly available via MAST.

We use the ‘raw’ (labelled as ‘AP_RAW_FLUX’ in the header) short-cadence (SC) data processed by the DR3 pipeline and a detailed description can be found in the accompanying release notes. The ‘raw’ data have been subject to photometric analysis (PA), which includes cleaning of cosmic ray hits, Argabrightenings, removal of background flux, aperture photometry and computation of centroid positions. It does not include Pre-search Data Conditioning (PDC) algorithm developed by the Data Analysis Working Group (DAWG). As detailed in DR3, these data are not recommended for scientific use, owing to, in part, the potential for underfitting/overfitting of the systematic effects.

2.2 Cleaning of the data

The raw data exhibit numerous systematic artefacts, including pointing tweaks (jumps in the photometry), safe mode recoveries (exponential decays) and focus drifts (long-term trends). The first effect may be corrected by applying an offset surrounding the jump, computed using a 30-point interpolative function either side. Due to the exponential nature of the second effect, we chose to exclude the affected data rather than attempt to correct it. The third effect may be corrected for using a detrending technique.

For this latter effect, we use the cosine filter utilized to detect ellipsoidal variations in CoRoT data by Mazeh & Faigler (2010). The technique acts as a high-pass filter allowing any frequencies of the orbital period or higher through, and all other long-term trends are removed. Thus, we protect any physical flux variations from any input mode as

\[ D_1 \]

Finally, we tried all three data input modes. In addition to the three models, we have three data input modes. The first is simply corrected for detrending and nothing else, denoted \( D_1 \). The second mode renormalizes each orbital period epoch. This renormalization is done by computing the median of each epoch and by dividing each segmented time series by this value, and we denote this mode as \( D_2 \). Finally, we tried allowing each orbital period epoch to have its own variable renormalization parameter, which is simultaneously fitted to the data along with the orbital phase curve model. This parameter is dubbed \( D_{\text{3.5}} \).

2.3 Three models

We first define our null hypothesis, \( M_1 \), where we employ a flat line model across the entire time series, described by a constant \( a_0 \). For a physical description of the orbital phase variations, we first tried the same model as that used by Sirko & Paczynski (2003) and Mazeh & Faigler (2010). This simple model is sufficient for cases where one is dealing with low S/N and reproduces the broad physical features. The model, \( M_2 \), is given by

\[
M_2(\phi) = a_0 + 0.5a_{1c} \cos(\phi) + a_{1c} \sin(\phi) + a_{2c} \cos(2\phi) + a_{2c} \sin(2\phi),
\]

where \( \phi \) is the orbital phase (defined as being 0 at the time of transit minimum) and \( a_i \) are coefficients related to the physical model. \( a_0 \) is simply a constant to remove any direct-current (DC) component in the data. \( a_{1c} \) corresponds to the reflection/emission effect and is expected to be a negative amplitude. \( a_{1c} \) corresponds to the relativistic beaming effect and is expected to be positive. \( a_{2c} \) corresponds to the ellipsoidal variations and

\[
0.5a_{1c} \cos \phi \rightarrow a_{1c} \left( \frac{\sin |\phi| + (\pi - |\phi|) \cos |\phi|}{\pi} \right).
\]

2.4 Three data modes

In addition to the three models, we have three data input modes. The first is simply corrected for detrending and nothing else, denoted \( D_1 \). The second mode renormalizes each orbital period epoch. This renormalization is done by computing the median of each epoch and by dividing each segmented time series by this value, and we denote this mode as \( D_2 \). Finally, we tried allowing each orbital period epoch to have its own variable renormalization parameter, which is simultaneously fitted to the data along with the orbital phase curve model. This parameter is dubbed \( D_{\text{3.5}} \) for the jth orbital period epoch. Denoting this data input mode as \( D_3 \), the fits now include an additional 51 free parameters.

The models are fitted to the unbinned data using a Markov chain Monte Carlo (MCMC) algorithm described in KB11 (method A), with 1.25 \times 10^6 accepted trials burning out the first 25 000. In total, there are nine ways of combining the three models with the three data modes. All nine models are fitted and results are given in Table 1, with our preferred model description being \( M_2 \), \( D_3 \) (since thermal emission is likely dominant over scattering, see Section 4).
3 RESULTS

3.1 Orbital photometry

Table 1 presents the results of fitting the detrended \textit{Kepler} photometry. Our models make no prior assumption on the sign or magnitude of the $a_i$ coefficients. The orbital period and transit epoch are treated as Gaussian priors from the circular orbit results of KB11.

When considering statistical significance, what one is really interested in is the confidence of detecting each physical effect, i.e. reflection/emission, ellipsoidal variations, beaming and the dummy term. Thus, any inference drawn from this would be for the entire model and not for each individual effect. In the analysis presented here, simple inspection of the posteriors from Fig. 2 shows that only one effect is actually detected (reflection/emission), but a model comparison method would evaluate the significance of all four physical effects (including the dummy term) versus no effect.

A more useful statistical test would consider the significance of each physical effect individually from a joint fit. An excellent tool to this end is the odds ratio test discussed in Kipping et al. (2010). If a parameter was equal to zero, we would expect 50 per cent of

| Model $\mathcal{M}$, Data $D$ | $a_{1c}$ (ppm) | $a_{1b}$ (ppm) | $a_{2c}$ (ppm) | $a_{2b}$ (ppm) | $\chi^2$ |
|-----------------------------|----------------|----------------|----------------|----------------|--------|
| $\mathcal{M}_1$, $D_1$      | 0\*            | 0\*            | 0\*            | 0\*            | 162 603.5431 |
| $\mathcal{M}_2$, $D_1$      | $-7.2_{-1.8}^{+1.8}$ | $0.78_{-0.85}^{+0.85}$ | $-1.4_{-0.92}^{+0.91}$ | $-0.27_{-0.85}^{+0.85}$ | 162 583.4014 |
| $\mathcal{M}_3$, $D_1$      | $-7.3_{-1.9}^{+1.8}$ | $0.79_{-0.86}^{+0.86}$ | $-0.77_{-0.91}^{+0.91}$ | $-0.26_{-0.86}^{+0.86}$ | 162 583.3162 |
| $\mathcal{M}_1$, $D_2$      | 0\*            | 0\*            | 0\*            | 0\*            | 161 875.4005 |
| $\mathcal{M}_2$, $D_2$      | $-6.4_{-1.8}^{+1.8}$ | $0.34_{-0.87}^{+0.86}$ | $-1.5_{-0.94}^{+0.93}$ | $0.19_{-0.87}^{+0.87}$ | 161 859.6732 |
| $\mathcal{M}_3$, $D_2$      | $-6.4_{-1.9}^{+1.8}$ | $0.34_{-0.86}^{+0.86}$ | $-0.94_{-0.92}^{+0.92}$ | $0.19_{-0.87}^{+0.87}$ | 161 859.6095 |
| $\mathcal{M}_1$, $D_3$      | 0\*            | 0\*            | 0\*            | 0\*            | 161 837.6648 |
| $\mathcal{M}_2$, $D_3$      | $-6.5_{-1.9}^{+1.9}$ | $0.22_{-0.87}^{+0.88}$ | $-1.5_{-0.93}^{+0.93}$ | $0.31_{-0.87}^{+0.87}$ | 161 821.7228 |
| $\mathcal{M}_3$, $D_3$      | $-6.7_{-1.8}^{+1.8}$ | $0.23_{-0.88}^{+0.89}$ | $-0.90_{-0.91}^{+0.91}$ | $0.32_{-0.88}^{+0.88}$ | 161 821.7232 |

Theory expectation | $-20 \rightarrow 0$ | $\sim 2.4$ | $\sim -2.3$ | 0 | – |

Figure 2: Top left-hand panel: final fit to the phased photometry. Points without errors are the 2000-point phase-binned data. Points with errors are 5000-point phase-binned data. Best-fitting model $\mathcal{M}_2$ with data mode $D_3$ shown in solid. Note that all fits were performed on the unbinned photometry. Top right-hand and lower panels: marginalized posterior distributions for the same model of four fitted parameters. Unity minus the false-alarm-probability values are provided for each parameter, based upon an odds ratio test described in Section 3.1.
the MCMC runs to give a positive value and 50 per cent to give a negative value. Consider that some asymmetry exists and a fraction $f$ of all MCMC trial were positive and $1-f$ were negative. The reverse could also be true, and so we define $f$ such that $f > 0.5$, i.e. it represents the majority of the MCMC trials. The odds ratio of the asymmetric model over the 50:50 model is

$$O = \frac{0.5}{1-f}.$$  \hspace{0.5cm} (3)

For only two possible models, the probability of the asymmetric model being the correct one is $P(\text{asym}) = 1 - [1/(1 + O)]$. We perform this test on each of the four parameters fitted for, $a_{1z}, a_{2z}, a_{1z}$, and $a_{2z}$. The associated results are visible in the top-left corners of each posterior shown in Fig. 2, for our preferred model and data mode, i.e. $M_{32}, D_{31}$. To summarize, only one parameter presents a significant detection – the reflection/emission effect. Here, we find that the posterior of $a_{1z}$ is sufficiently asymmetric to have a probability of occurring by random chance of just 0.02 per cent, which equates to $3.67\sigma$. We consider any signal detected above $3\sigma$ confidence to merit the claim of a ‘detection’ rather than a measurement, and thus we find TrES-2b to be the darkest exoplanet from which visible light has been detected.

As discussed in Section 2.3, we tried two different models for the reflection/emission effect: a simple sinusoid ($M_{32}$) and the reflected light from a perfectly Lambertian sphere ($M_{41}$). Between the two models, there is negligible difference in the goodness of fit, as seen in Table 1, for all three data modes. Including the Lambertian model takes some power away from the ellipsoidal variations though, and thus the current data do not yield a preference between a Lambertian sphere model or stronger ellipsoidal variations.

3.2 Occultation measurement

The duration of the transit, and thus occultation since TrES-2b maintains negligible eccentricity, is equal to $4624 \pm 42$ s (defined as the time between the planet’s centre crossing the stellar limb and exiting under the same condition). In contrast, the orbital period of TrES-2b is $2470.619$ d. We therefore obtain $\sim46$ times more integration time of the orbit than the occultation event. This indicates that we should expect to be able to reach a sensitivity of $\sqrt{46}$ times greater, purely from photon statistics. The uncertainty on our phase curve measurement is $\pm1.9$ ppm. We therefore estimate that one should have an uncertainty on the occultation depth of $\sim13$ ppm. If we assume the nightside has a negligible flux, then the depth of the occultation is expected to be 6.5 ppm (i.e. equal to the day–night contrast), and this already suggests that the present publicly available Kepler photometry will be insufficient to detect the occultation. To test this hypothesis, we will here fit the occultation event including the Q0, Q1 and Q2 data.

To perform our fit, we use the same Gaussian priors on $P$ and $\tau$ as earlier. We also adopt priors for other important system parameters from KB11, such as $b=0.8408 \pm 0.0050$, $p^2=1.643 \pm 0.067$ per cent and $T_1=4624 \pm 42$ s. We stress that these are all priors and not simply fixed parameters. We also make use of the priors on the $a_{0j}$ coefficients from the $M_{31}, D_{31}$ fit. Data are trimmed to be within $\pm0.06$ d of the expected time of occultation to prevent the phase curve polluting our signal, leaving us with 8457 SC measurements. Assuming a circular orbit, the data were fitted using an MCMC algorithm.

The marginalized posterior of the occultation depth yields $\delta_{\text{occ}} = 16^{+15}_{-14}$ ppm, which is clearly not a significant detection. The derived uncertainty of 13–14 ppm is very close to our estimation of $\sim13$ ppm and thus supports our hypothesis that the current Kepler data are insufficient to detect the occultation of TrES-2b. We also note that the inclusion of the Q2 data does improve the constraints on the occultation event (KB11 found $\delta_{\text{occ}} = 21^{+13}_{-12}$ ppm using Q0 and Q1 only).

4 DISCUSSION

Hot Jupiters are generally expected to be dark. Significant absorption due to the broad wings of the sodium and potassium D lines is thought to dominate their visible spectra (Sudarsky, Burrows & Pinto 2000), leading to low albedos of a few percent. Indeed, aside from the recent report of Kepler-7b’s (38 $\pm$ 12 per cent Kepler-band geometric albedo (KB11), searches for visible light from hot Jupiters have generally revealed mere upper limits (Collier Cameron et al. 2002; Leigh et al. 2003; Burrows, Ibugi & Hubeny 2008; Rowe et al. 2008).

The $6.5 \pm 1.9$ ppm contrast (determined from our preferred model $M_{32}, D_{31}$) between the dayside and nightside photon flux that we measure for TrES-2b represents the most sensitive measurement yet of emergent radiation in the visible from a hot Jupiter, and is a factor of $\sim20$ and $\sim6$ dimmer than the corresponding differences for HAT-P-7b (Welsh et al. 2010) and Kepler-7b, respectively.

In order to interpret the visible flux, we use the planetary atmosphere modelling code C O O L T L U S T Y (Hubeny, Burrows & Sudarsky 2003). For simplicity, we adopt equilibrium chemistry with nearly solar abundance of elements, although we leave titanium oxide and vanadium oxide (TiO and VO, respectively) out of the atmosphere model. These compounds could, if present in the upper atmosphere of a hot Jupiter, strongly affect the atmosphere structure and the visible and near-infrared (near-IR) spectra by making the atmosphere more opaque in the visible and by leading to a thermal inversion if the stellar irradiation exceeds $\sim10^9$ erg cm$^{-2}$ s$^{-1}$ (Hubeny et al. 2003; Fortney et al. 2008). We leave TiO and VO out of our calculations, however, because of the difficulty of maintaining heavy, condensable species high in the atmospheres (Spiegel, Silverio & Burrows 2009). Instead, we use an ad hoc extra opacity source $\kappa^*$, as described in Spiegel & Burrows (2010).

We calculate a grid of models with $\kappa^*$ ranging (in cm$^2$ g$^{-1}$) from 0 to 0.6 in steps of 0.1 and with redistribution $P^r$, ranging from 0 to 0.5 in steps of 0.1 ($P$ represents the fraction of incident irradiation that is transported to the nightside, which is assumed in our models to occur in a pressure range from 10 to 100 mbar). For each of these 42 parameter combinations, we calculate a dayside model, a nightside model and a model that has the same temperature/pressure structure as the dayside but that has the star turned off, so as to calculate the emitted (and not scattered) flux (thus also giving the scattered component).

We draw several inferences from our models and the data. First, the nightside contributes negligible flux in the Kepler band (always <12 per cent of the dayside, and for most models significantly less than that), meaning that the 6.5-ppm number represents essentially the entire dayside flux.

Secondly, by also including the available infrared secondary eclipse data on TrES-2b (Croll et al. 2010; O’Donovan et al. 2010), we find that in our model set, there must be some redistribution (but not too much) and there must be some extra absorber (but not too much). For each model, we compute a $\chi^2$ value, including six data points: Kepler band, $K_1$ band and the four Spitzer IRAC channels (3.6, 4.5, 5.8 and 8.0 $\mu$m). Fig. 3 portrays the $\chi^2$ values of our grid of models, with the colour ranges corresponding to the $\chi^2$ values bounding 68.3 per cent of the integrated probability (1$\sigma$),
Figure 3. Goodness of fit for a grid of atmosphere models. The models that are consistent with available Kepler band, Ks band, and Spitzer IRAC data have moderate redistribution to the nightside (Pn) and moderate extra optical opacity (κ'). Models with κ' = 0 can be ruled out on the basis of the Kepler data alone.

95.5 per cent (2σ), 99.7 per cent (3σ) and 99.99 per cent (4σ). The models that best explain the available data correspond to κ' ≈ 0.3–0.4 cm² g⁻¹ and Pn ≈ 0.3 (~30 per cent of incident flux redistributed to the night). In particular, models with no extra absorber are completely inconsistent with observations, even on the basis of the Kepler data alone. The upshot is that some extra opacity source appears to be required to explain the emergent radiation from this extremely dark world. Owing to this optical opacity, our models that are consistent with the data have thermal inversions in their upper atmosphere, as in Spiegel & Burrows (2010). We note that Madhusudhan & Seager (2010) find that the IR data of TrES-2b may be explained by models both with and without thermal inversions; nevertheless, we believe that optical opacity sufficient to explain the Kepler data is likely to heat the upper atmosphere, as per Hubeny et al. (2003).

Finally, by computing the scattered contribution to the total flux, we find that for all parameter combinations, the scattered light contributes ≲ 10 per cent of the Kepler-band flux, and for the best-fitting models the scattered light is ≲ 1.5 per cent of the total. TrES-2b, therefore, appears to have an extremely low geometric albedo (for all models, the geometric albedo is < 1 per cent, and for the best-fitting models it is ~ 0.04 per cent). Exact values for the amount of extra optical opacity, redistribution and the albedo cannot be presently provided because inferences about them depend on unknown quantities such as the wavelength dependence of the extra opacity source and the altitude dependence of winds.

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