

An extremely high photometric precision in ground-based observations of two transits in the WASP-50 planetary system

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ABSTRACT

We present photometric observations of two transits in the WASP-50 planetary system, obtained using the ESO New Technology Telescope and the defocused-photometry technique. The rms scatters for the two data sets are 258 and 211 ppm with a cadence of 170–200 s, setting a new record for ground-based photometric observations of a point source. The data were modelled and fitted using the PRISM and GEMC codes, and the physical properties of the system calculated. We find the mass and radius of the hot star to be $0.861 \pm 0.057 M_{\odot}$ and $0.855 \pm 0.019 R_{\odot}$, respectively. For the planet we find a mass of $1.437 \pm 0.068 M_{\text{Jup}}$, a radius of $1.138 \pm 0.026 R_{\text{Jup}}$ and a density of $0.911 \pm 0.033 \rho_{\text{Jup}}$. These values are consistent with but more precise than those found in the literature. We also obtain a new orbital ephemeris for the system: $T_0 = \text{BJD/TDB } 245\,5558.612\,37(20) + 1.955\,0938(13) \times E$.

Key words: techniques: photometric – stars: fundamental parameters – stars: individual: WASP-50 – planetary systems.

1 INTRODUCTION

Mayor & Queloz (1995) discovered the first planet orbiting a normal star outside our own Solar system, 51 Peg, from radial velocity (RV) measurements. The first transiting planet was found using photometric observations of a system, HD 209458, already known from RV measurements to host a planet (Charbonneau et al. 2000; Henry et al. 2000). OGLE-TR-56 was the first planet discovered from its transits (Udalski et al. 2002; Konacki et al. 2003). The transit detection method uses photometry to measure the change in received flux from a star when a planet crosses the stellar disc. Since then, ground-based transit detection surveys such as Wide Angle Search for Planets (WASP) (Pollacco et al. 2006) and Hungarian Automated Telescope (Bakos et al. 2004) have been set up around the world. Once a survey has discovered a transiting extrasolar planet (TEP), follow-up spectroscopic and photometric observations are required to properly characterize the system.

To achieve high-precision photometry requires not only a high signal-to-noise ratio (S/N) but also nullification of many systematic effects inherent in ground-based photometry. Southworth et al. (2009a) investigated the use of defocused telescopes to obtain high-precision photometry. Telescope defocusing causes the light from point sources to be distributed over thousands of CCD pixels. This allows the use of longer exposure times, which means that the CCD is read out less often. This reduced dead time means that more photons can be collected over a given time interval, leading to lower Poisson and scintillation noise. Flat-fielding noise also averages down by an order of magnitude due to the large number of pixels

in the software aperture, and changes in seeing become inconsequential. Many researchers have used the technique of defocused photometry to obtain precise measurements of the parameters of TEP systems (e.g. Demory et al. 2007; Gillon et al. 2007, 2008; Winn et al. 2007a,b). We note that the defocusing technique is only suitable for bright isolated stars. If a star is too faint, then the increased background and read-out noise can be detrimental. If the target and comparison stars are in a crowded field, then defocusing will cause their point spread functions (PSF) to become blended with those of nearby stars.

The discovery of the TEP system WASP-50 was presented by Gillon et al. (2011), who found it to comprise a TEP with a mass of $1.47 \pm 0.09 M_{\text{Jup}}$ and radius of $1.15 \pm 0.05 R_{\text{Jup}}$, orbiting a cool star with mass and radius $0.89 \pm 0.08 M_{\odot}$ and $0.84 \pm 0.03 R_{\odot}$, respectively. We observed WASP-50 with the aim of improving its measured physical properties, using the telescope-defocusing approach. We used the New Technology Telescope (NTT) operated by ESO at La Silla, Chile. This telescope is alt-az mounted and has a thin primary mirror whose shape is maintained using active optics. Whilst these qualities are not outwardly well suited to the telescope-defocusing approach, we have previously found the NTT to work well for this type of observations (Hellier et al. 2011; Tregloan-Reed, Southworth & Tappert 2013). We observed two complete transits of WASP-50 using the NTT, achieving extremely low photometric scatters of 258 and 211 ppm, respectively, versus a fitted model. To our knowledge the latter is the lowest scatter ever achieved in ground-based photometry per point for a point source.

Some of the highest photometric precisions previously accomplished for a TEP system are 479 ppm for CoRoT-1 using the 8.2 m VLT (Pont et al. 2010), 478 ppm for WASP-4 using the 6.5 m Magellan Baade telescope (Winn et al. 2009), 470 ppm for

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Table 1. Log of the observations presented in this work. N_{obs} is the number of observations. ‘Moon illum.’ and ‘Moon dist.’ are the fractional illumination of the Moon, and its distance from WASP-50 in degrees, at the mid-point of the transit.

Date	Start time (UT)	End time (UT)	N_{obs}	Exposure time (s)	Filter	Airmass	Moon illum.	Moon dist.	Aperture sizes (pixel)	Scatter (ppm)
2011-11-20	00:59	06:02	127	120–150	Gunn <i>r</i>	2.62 → 1.48	0.384	91.2	75, 105, 120	258
2011-11-24	01:08	06:27	124	150	Gunn <i>r</i>	2.10 → 1.53	0.045	137.4	75, 100, 125	211

WASP-10 using the University of Hawaii 2.2 m telescope (Johnson et al. 2009), 387 ppm for WASP-2 using a 1.5 m telescope (Southworth et al. 2010) and 316 ppm for TrES-2 using the 10.4 m Gran Telescopio Canarias (Colón et al. 2010). The highest photometric precision we are aware of from a ground-based telescope was previously 258 ppm in time series observations of stars in the open cluster M67 (Gilliland et al. 1993).

An alternative metric which is well-suited to direct comparison is S/N per unit time. We have calculated the scatter in parts per million per minute of observing time for the data sets listed above. By this metric the better of our two data sets is almost exactly equal to the best one presented by Gilliland et al. (1993), and both of our light curves are better than any previously published ground-based photometric observations of a TEP system.

2 OBSERVATIONS AND DATA REDUCTION

Two transits of WASP-50 were observed on the nights of 2011 November 20 and 24 using the NTT with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) instrument operated in imaging mode. In this setup the CCD covers a field of view of $(4.1 \text{ arcmin})^2$ with a plate scale of $0.12 \text{ arcsec pixel}^{-1}$. The images were windowed down to 1100×1600 pixels and no binning was used, resulting in a dead time between consecutive images of 50 s. The observations were taken through a Gunn *r* filter (ESO filter #784). The moon was below the horizon for half of the first transit and all of the second transit. The telescope was initially focused and the shape of its primary mirror was adjusted to obtain the best image possible. We then applied a defocus to the telescope and performed the full observing sequence without adjusting the telescope focus or mirror shape.

The pointing of the telescope was adjusted to allow a good comparison star to be observed simultaneously with WASP-50. The comparison star used was 2MASS J02544939–1051548, which is of a similar apparent magnitude and colour to WASP-50. The 2MASS $J - K_s$ colour indices of the two objects are 0.432 for WASP-50 and 0.357 for the comparison star (Skrutskie et al. 2006). We were able to keep the telescope autoguided through all observations. An observing log is given in Table 1.

Fig. 1 shows the shape of the PSF of WASP-50 in an image taken at random from the observing sequence on the night of 2011 October 24. Fig. 1 provides an interesting comparison with similar observations of WASP-4 and WASP-5 from a 1.5 m telescope of more traditional design (see fig. 1 in Southworth et al. 2009a and fig. 1 in Southworth et al. 2009b). The PSF for the current observations shows a much more rounded annulus of high counts, which allows a smaller amount of defocusing to be used to collect a given number of photons without saturating individual pixels.

We reduced the data in an identical fashion to Southworth et al. (2009a). In short, we performed aperture photometry using an IDL implementation of DAOPHOT (Stetson 1987), and adjusted the aperture sizes to obtain the best results (see Table 1). A differential-magnitude light curve was calculated between the target and com-

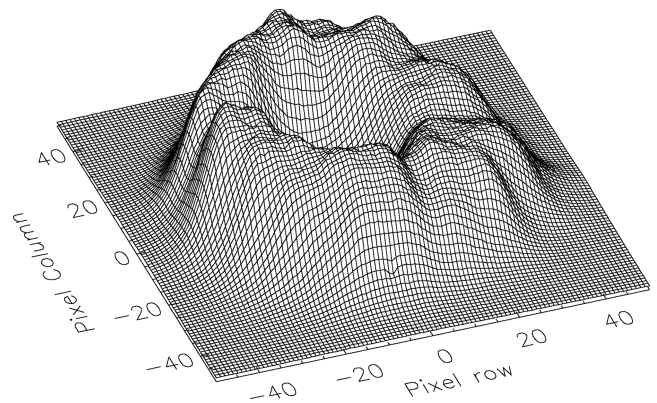


Figure 1. Surface plot of the PSF of WASP-50 in an image taken at random from the observing sequence on the night of 2011 October 24. The x and y axes are in pixels. The lowest and highest counts are 684 and 24 726 ADUs, respectively, and the z axis is on a linear scale.

parison star. A first-order polynomial was then fitted to the outside-transit data and then subtracted to remove a slow trend present in the differential magnitudes. The times of the start of the exposures were given in JD/UTC in the Flexible Image Transport System file headers, and we converted these to times of the mid-points of the exposures in BJD/TDB.

In order to confirm the low scatter of the resulting light curves we performed a second data reduction with completely different methods. We used the Starlink/AUTOPHOT package (Eaton, Draper & Allen 1999) driven by a custom C-shell script (Southworth, Maxted & Smalley 2004a), and obtained a light curve with an rms scatter of 414 ppm for the first night of data. This result agrees with our light curve from DAOPHOT, once the discretization of the data points (AUTOPHOT quotes instrumental magnitudes to only three decimal places) is taken into account.

3 DATA ANALYSIS

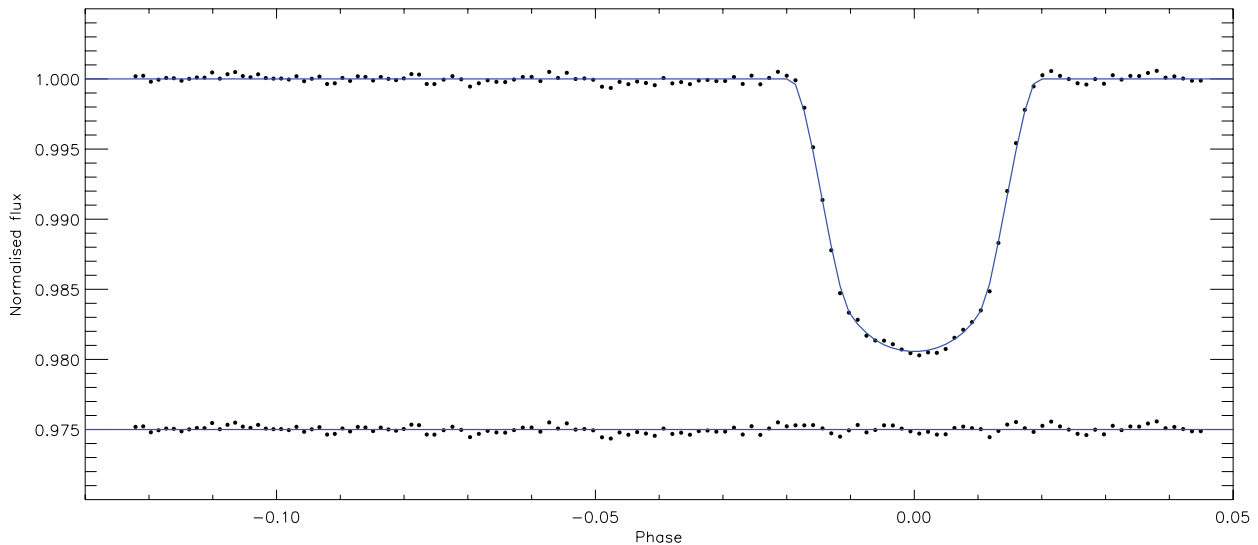
We fitted the WASP-50 data in a similar manner to Tregloan-Reed et al. (2013). Planetary Retrospective Intergrated Starspot Model (PRISM)¹ was used to model the transit. PRISM uses a pixelation approach to represent the star and planet on a two-dimensional array in Cartesian coordinates. This makes it possible to model the transit, limb darkening and starspots on the stellar disc simultaneously. Limb darkening was implemented using the standard quadratic law. PRISM used the six parameters given in Table 2 to model the system, where the fractional stellar and planetary radii are defined as the absolute radii scaled by the semimajor axis ($r_{s,p} = R_{s,p}/a$).

Genetic Evolution Markov Chain (GEMC)¹ was used to fit the model to the data. GEMC begins by randomly generating parameters for the starting points of N chains, within the user-defined parameter

¹ Available from <http://www.astro.keele.ac.uk/~jtr>.

Table 2. Derived photometric parameters from each light curve, plus the interval within which the best fit was searched for using GEMC.

Parameter	Symbol	Search interval	2011-11-20	2011-11-24	Combined photometric parameters
Radius ratio	r_p/r_s	0.05–0.30	$0.137\ 10 \pm 0.000\ 49$	$0.136\ 61 \pm 0.000\ 36$	$0.136\ 78 \pm 0.000\ 29$
Sum of fractional radii	$r_s + r_p$	0.10–0.50	0.1552 ± 0.0018	0.1553 ± 0.0016	0.1552 ± 0.0012
Linear LD coefficient	u_1	0.0–1.0	0.386 ± 0.068	0.385 ± 0.049	0.386 ± 0.040
Quadratic LD coefficient	u_2	0.0–1.0	0.281 ± 0.099	0.279 ± 0.043	0.280 ± 0.040
Inclination (degrees)	i	70.0–90.0	84.43 ± 0.17	84.45 ± 0.14	84.44 ± 0.11
Transit epoch (BJD/UTC)	T_0	± 0.5 in phase	$245\ 5855.781\ 72 \pm 0.000\ 076$	$245\ 5859.691\ 755 \pm 0.000\ 118$	

**Figure 2.** Transit light curve and the best-fitting model for 2011 November 20. The residuals are displayed at the base of the figure.

space, and then simultaneously evolves the chains for X generations. At each generation the chains are evaluated for their fitness.² The parameters of the fittest member undergo a maximum ± 1 percent perturbation and its fitness is then re-evaluated. If the fitness has improved, it is accepted but if the fitness has deteriorated it may or may not be accepted based on a Gaussian probability distribution:

$$P = \exp\left(\frac{(\chi_{(n-1)}^2 - \chi_n^2)}{2}\right), \quad (1)$$

where $(n - 1)$ is the previous generational chain and n is the current generational chain being evaluated. The next step is to evolve the other chains. This is accomplished in a similar way as a genetic algorithm, in that the chain parameters are modified by incorporating the parameters of another chain. But unlike a genetic algorithm where a member is picked by a weighted random number and then the digits of each parameter are crossed over with the digits from a different member, GEMC directly perturbs the parameters of each chain in a vector towards the best-fitting chain. The size of this perturbation is between zero and twice the distance to the best-fitting chain, allowing the chain to not only move towards but also to overshoot the position of the best-fitting chain. This continues until all the chains have converged around the optimal solution. Once the burn-in phase has been completed the chains cease communication and begin independent Markov Chain runs.

Because GEMC is a hybrid between the Markov Chain Monte Carlo approach and a genetic algorithm, the burn-in phase is relatively short, allowing us to use a large parameter search space.

The boundaries of the search space for each parameter are given in Table 2, which also contains the individual results for the two light curves. Table 2 also gives the final photometric parameters for the WASP-50 system, which are weighted means of the results from the two individual fits. All error bars denote 1σ uncertainties. Figs 2 and 3 compare the light curves to the best-fitting models, including the residuals. The two data sets were modelled individually, and the agreement between the best-fitting parameters is exceptionally good. The best-fitting limb-darkening coefficients are also in good agreement with the theoretically predicted values for WASP-50 A of $u_1 = 0.407$ and $u_2 = 0.281$ (Claret 2004). Our data were taken with 120 and 150 s exposures, so we have checked whether these relatively long exposure times affect the derived parameters. For this we modelled the data using the JKTEBOP code (Southworth, Maxted & Smalley 2004b), finding results in good agreement with those from PRISM. We then used JKTEBOP's option to numerically integrate the model over the duration of each exposure whilst finding the best fit (Southworth 2011). The final parameters for each light curve altered by only 0.1 – 0.25σ , allowing us to conclude that smearing of the transit shape due to long exposure times does not have a significant effect on our results.

To check for correlated 'red' noise we used the Monte Carlo and residual-permutation algorithms in JKTEBOP (Southworth 2008) to assess the uncertainties in the fitted parameters. We found a difference between the two methods of only 0.1 percent, and conclude that the correlated noise is not present at a significant level in our data.

We also used JKTEBOP to check whether the removal of the slow drift in brightness with a first-order polynomial had any effect on our results. We found that including the polynomial coefficients as

² A solution's fitness was found by calculating the $1/\chi^2$ value.

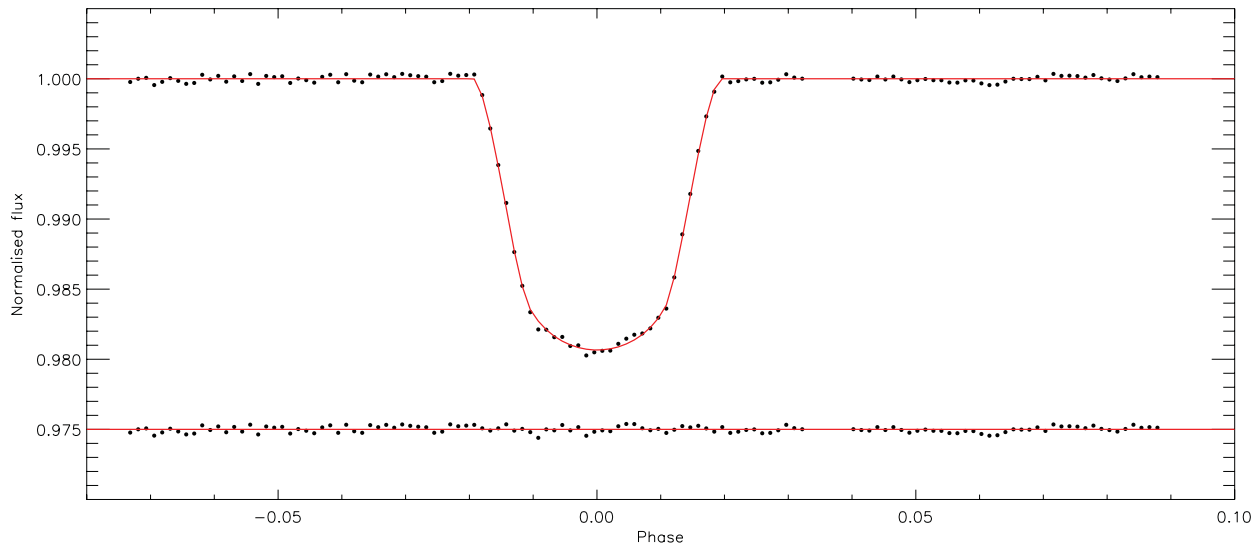


Figure 3. Transit light curve and the best-fitting model for 2011-11-24. The residuals are displayed at the base of the figure. The gap in the data between phases 0.03 and 0.04 was caused by a technical difficulty with the shutter on EFOSC2. This was corrected by a shutdown and restart of the instrument. The telescope pointing was unaffected.

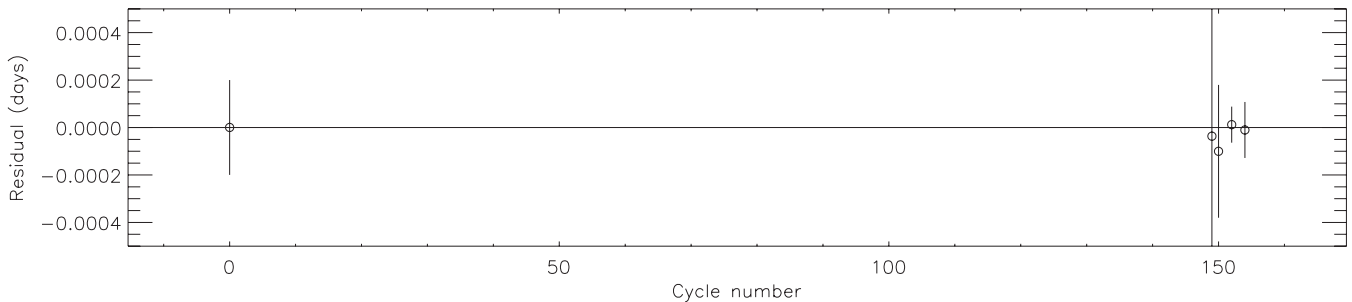


Figure 4. Residuals of the available times of mid-transit versus the orbital ephemeris found in this work. The two timings from this work are the last two points after cycle number 150.

fitted parameters caused changes in the other parameters of roughly 0.001σ . We conclude that the detrending process has had no deleterious effect on our results.

We have collected the available times of mid-transit for WASP-50 from the literature (Gillon et al. 2011; Sada et al. 2012). All timings were converted to the BJD/TDB time-scale and used to obtain an improved orbital ephemeris:

$$T_0 = \text{BJD/TDB } 245\,5558.61237(20) + 1.955\,0938(13) \times E,$$

where E represents the cycle count with respect to the reference epoch and the bracketed quantities represent the uncertainty in the final digit of the preceding number. Fig. 4 and Table 3 show the residuals of these times against the ephemeris. We find no evidence for transit timing variations in the system.

3.1 Physical properties of the WASP-50 system

Once the photometric parameters of WASP-50 had been measured, we moved to the determination of its physical characteristics. We adopted the approach of Southworth (2009), which uses the parameters measured from the light curves and spectra, plus tabulated predictions of several theoretical models. We adopted the values of i , r_p/r_s and $r_s + r_p$ from Table 2, and the stellar properties of effective temperature $T_{\text{eff}} = 5400 \pm 100$ K, metal abundance

Table 3. Times of minimum light of WASP-50 and their residuals versus the ephemeris derived in this work.

Time of minimum (BJD/TDB – 240 0000)	Cycle no.	Residual (BJD)	Reference
555 58.612 37 ± 0.000 20	0.0	0.000 00	1
558 49.921 31 ± 0.000 60	149.0	–0.000 04	2
558 51.876 34 ± 0.000 28	150.0	–0.000 10	2
558 55.786 64 ± 0.000 08	152.0	0.000 01	3
558 59.696 80 ± 0.000 12	154.0	–0.000 01	3

References: (1) Gillon et al. (2011); (2) Sada et al. (2012); (3) This work.

$[\text{Fe}/\text{H}] = -0.12 \pm 0.08$ and velocity amplitude $K_s = 256.6 \pm 4.4 \text{ m s}^{-1}$ (Gillon et al. 2011).

An initial value of the velocity amplitude of the planet, K_p , was used to calculate the physical properties of the system using standard formulae and the physical constants listed by Southworth (2011). The mass and $[\text{Fe}/\text{H}]$ of the star were then used as interpolates within tabulated predictions from stellar theoretical models, in order to find the expected T_{eff} and radius. K_p was then iteratively refined to find the best agreement between the observed and predicted T_{eff} , and the light-curve-derived r_s and predicted R_s/a . This was performed for ages ranging from zero age to the terminal-age main sequence, in steps of 0.01 Gyr. The overall best fit was

Table 4. Physical properties of the WASP-50 system. The equilibrium temperature, T'_{eq} , is for an assumed zero albedo and full heat redistribution. Θ is the Safronov (1972) number.

Parameter	This work	Gillon et al. (2011)
$M_A (M_{\odot})$	$0.861 \pm 0.052 \pm 0.023$	$0.892^{+0.080}_{-0.074}$
$R_A (R_{\odot})$	$0.855 \pm 0.018 \pm 0.007$	0.843 ± 0.031
$\log g_A$ (cgs)	$4.509 \pm 0.012 \pm 0.004$	4.537 ± 0.022
$\rho_A (\rho_{\odot})$	1.376 ± 0.032	$1.48^{+0.10}_{-0.09}$
$M_b (M_{\text{Jup}})$	$1.437 \pm 0.063 \pm 0.025$	$1.468^{+0.091}_{-0.086}$
$R_b (R_{\text{Jup}})$	$1.138 \pm 0.024 \pm 0.010$	1.153 ± 0.048
g_b (m s^{-2})	27.50 ± 0.64	27.5 ± 1.6
$\rho_b (\rho_{\text{Jup}})$	$0.911 \pm 0.032 \pm 0.008$	$0.958^{+0.095}_{-0.082}$
T'_{eq} (K)	1410 ± 26	1393 ± 30
Θ	$0.0853 \pm 0.0024 \pm 0.0007$	
a (au)	$0.029\ 13 \pm 0.000\ 59 \pm 0.000\ 25$	$0.029\ 45 \pm 0.000\ 85$
Age (Gyr)	$8.1^{+6.7+1.5}_{-4.4-1.3}$	

identified, yielding estimates of the physical properties of the system and the evolutionary age of the star. This procedure was performed separately using five different sets of stellar theoretical models (see Southworth 2010), and the spread of values for each output parameter was used to determine a systematic error. Statistical errors were propagated by perturbing each input parameter in turn to quantify the effect on each output parameter.

The final results of this process have good internal agreement (between the five sets of theoretical models) and are also consistent with those found by Gillon et al. (2011). The final physical properties are given in Table 4 and include separate statistical and systematic error bars for those parameters with a dependence on the theoretical models. The final statistical error bar for each parameter is the largest of the individual ones from the solutions using each of the five different stellar models. The systematic error bar is the largest difference between the mean and the individual values of the parameter from the five solutions.

4 SUMMARY AND DISCUSSION

In the pursuit of obtaining accurate properties for transiting extra-solar planetary systems we have achieved photometric precisions of 258 and 211 ppm in observations of WASP-50, which to our knowledge is a record for ground-based photometry of a point source. Our approach was to heavily defocus the 3.6 m NTT and to use exposure times of 120–150 s. We also benefitted from the presence of a good comparison star, at a distance of 2.25 arcmin from WASP-50 and with similar colours and r -band apparent magnitude. The sky brightness was also low, as the moon was below the horizon for most of our observations.

We reduced our data using two independent pipelines, finding agreement between them. We modelled the light curves using the PRISM and JKTEBOP codes, again finding good agreement. From these results and published spectroscopic measurements we have deduced the physical properties of the WASP-50 system to high precision. The properties of the planet WASP-50 b are now known to be within 5 per cent (mass), 2 per cent (radius), 4 per cent (density) and 2 per cent (surface gravity). This compares to 6, 4, 9 and 6 per cent, respectively, in the discovery paper (Gillon et al. 2011). We also obtained a refined orbital ephemeris. Further improvements in precision could be made in the shorter term by obtaining additional radial velocity measurements, and in the longer term by using sets

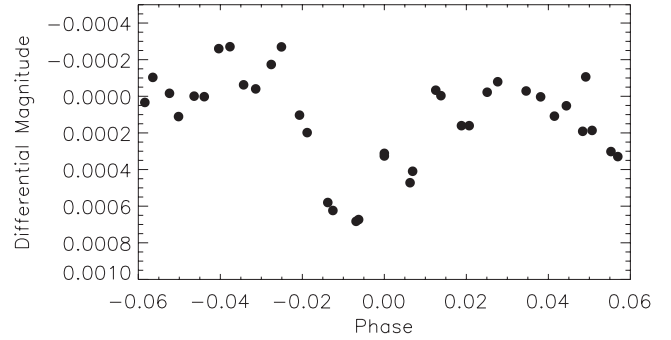


Figure 5. Simulated light curve of a $2 R_{\oplus}$ planet orbiting WASP-50 A.

of stellar models which show a better inter-agreement on properties of the host star WASP-50 A.

In our study of WASP-19 (Tregloan-Reed et al. 2013) we found a modest discrepancy between limb-darkening coefficients measured from three data sets taken with the same telescope. This was attributed to the fact that WASP-19 A is an active star with significant starspot activity, which alters the limb-darkening behaviour of the star (Ballerini et al. 2012). Whilst WASP-50 does show modest chromospheric activity, as judged from emission in the Ca II H&K lines (Gillon et al. 2011), starspot anomalies have not been observed in any of the five transit light curves of this system. The limb-darkening coefficients found from our two data sets are in excellent agreement (0.02σ), supporting the suggestion that starspots affect stellar limb darkening.

Finally, we have checked if observations of this high precision could be used to characterize transiting super-Earths. We injected a synthetic transit of a $2 R_{\oplus}$ planet in front of WASP-50 A into the residuals of our best fits from both nights, and binned the data together. This simulated light curve (Fig. 5) shows a clear transit signature, suggesting that ground-based defocused photometry of transiting super-Earths is a viable possibility.

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We like to thank the anonymous referee for the helpful comments on the manuscript. The reduced light curves presented in this work will be made available at the CDS (<http://cdsweb.u-strasbg.fr/>) and at both <http://www.astro.keele.ac.uk/~jtr/> and <http://www.astro.keele.ac.uk/~jkt/>. This paper used data collected from the New Technology Telescope at the European Southern Observatory, Chile, programme number 088.C-0204(A). JTR acknowledges financial support from STFC in the form of a PhD studentship. JS acknowledges financial support from STFC in the form of an Advanced Fellowship.

REFERENCES

- Bakos G., Noyes R. W., Kovács G., Stanek K. Z., Sasselov D. D., Domsa I., 2004, *PASP*, 116, 266
- Ballerini P., Micela G., Lanza A. F., Pagano I., 2012, *A&A*, 539, A140
- Charbonneau D., Brown T. M., Latham D. W., Mayor M., 2000, *ApJ*, 529, L45
- Claret A., 2004, *A&A*, 428, 1001
- Colón K. D., Ford E. B., Lee B., Mahadevan S., Blake C. H., 2010, *MNRAS*, 408, 1494
- Demory B.-O. et al., 2007, *A&A*, 475, 1125
- Eaton N., Draper P. W., Allen A., 1999, *Starlink User Note* 45.9 (<http://www.starlink.rl.ac.uk/docs/sun45.htx/node33.html>)
- Gilliland R. L. et al., 1993, *AJ*, 106, 2441

- Gillon M. et al., 2007, *A&A*, 472, L13
 Gillon M., Triaud A. H. M. J., Mayor M., Queloz D., Udry S., North P., 2008, *A&A*, 485, 871
 Gillon M. et al., 2011, *A&A*, 533, A88
 Hellier C., Anderson D. R., Collier-Cameron A., Miller G. R. M., Queloz D., Smalley B., Southworth J., Triaud A. H. M. J., 2011, *ApJ*, 730, L31
 Henry G. W., Marcy G. W., Butler R. P., Vogt S. S., 2000, *ApJ*, 529, L41
 Johnson J. A., Winn J. N., Cabrera N. E., Carter J. A., 2009, *ApJ*, 692, L100
 Konacki M., Torres G., Jha S., Sasselov D. D., 2003, *Nat*, 421, 507
 Mayor M., Queloz D., 1995, *Nat*, 378, 355
 Pollacco D. L. et al., 2006, *PASP*, 118, 1407
 Pont F. et al., 2010, *MNRAS*, 402, L1
 Sada P. V. et al., 2012, *PASP*, 124, 212
 Safronov V. S., 1972, *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets*. Israel Program for Scientific Translation, Jerusalem
 Skrutskie M. F. et al., 2006, *AJ*, 131, 1163
 Southworth J., 2008, *MNRAS*, 386, 1644
 Southworth J., 2009, *MNRAS*, 394, 272
 Southworth J., 2010, *MNRAS*, 408, 1689
 Southworth J., 2011, *MNRAS*, 417, 2166
 Southworth J., Maxted P. F. L., Smalley B., 2004a, *MNRAS*, 349, 547
 Southworth J., Maxted P. F. L., Smalley B., 2004b, *MNRAS*, 351, 1277
 Southworth J. et al., 2009a, *MNRAS*, 396, 1023
 Southworth J. et al., 2009b, *MNRAS*, 399, 287
 Southworth J. et al., 2010, *MNRAS*, 408, 1680
 Stetson P. B., 1987, *PASP*, 99, 191
 Tregloan-Reed J., Southworth J., Tappert C., 2013, *MNRAS*, 428, 3671
 Udalski A., Zebur K., Szymanski M., Kubiak M., Soszynski I., Szewczyk O., Wyrzykowski L., Pietrzynski G., 2002, *Acta Astron.*, 52, 115
 Winn J. N. et al., 2007a, *AJ*, 133, 1828
 Winn J. N. et al., 2007b, *AJ*, 134, 1707
 Winn J. N., Holman M. J., Carter J. A., Torres G., Osip D. J., Beatty T., 2009, *AJ*, 137, 3826

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