Updated parameters for the transiting exoplanet WASP-3b using RISE, a new fast camera for the Liverpool Telescope

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ABSTRACT

Some of the first results are reported from RISE – a new fast camera mounted on the Liverpool Telescope primarily designed to obtain high time-resolution light curves of transiting extrasolar planets for the purpose of transit timing. A full and partial transit of WASP-3 are presented, and a Markov-Chain Monte Carlo analysis is used to update the parameters from the discovery paper. This results in a planetary radius of $1.29^{+0.05}_{-0.12}\ R_J$ and therefore a density of $0.82^{+0.14}_{-0.09}\ \rho_J$, consistent with previous results. The inclination is $85.06^{+0.16}_{-0.15}$ deg, in agreement (but with a significant improvement in the precision) with the previously determined value. Central transit times are found to be consistent with the ephemeris given in the discovery paper; however, a new ephemeris calculated using the longer baseline results in $T_c(0) = 2\,454\,605.55915 \pm 0.00023$ HJD and $P = 1.846835 \pm 0.000002$ days.

Key words. methods: data analysis – stars: planetary systems – stars: individual: WASP-3 – techniques: photometric

1. Introduction

Transit observations of extrasolar planets are vital to our understanding of planetary systems, as they allow us to determine the orbital inclination and planetary radius, and when coupled with the radial velocity (RV) method, the mass and density may be derived. Ground-based transit surveys such as SuperWASP (Pollacco et al. 2006) and HATnet (Bakos et al. 2004) are now coming of age, and to date over 50 transiting planets have been found[1]. Most of these systems are Hot Jupiters (with the exception of GJ-436b – see Gillon et al. 2007), and neither these transit surveys nor the RV method are close to reaching the required precision to search for Earth-sized planets.

However, high precision transit photometry may provide us with a short-cut to detecting Earth-sized planets around existing transiting systems, as it allows us to measure the central transit times of these systems very accurately. This could reveal the presence of a third body through transit timing variations (TTV) by measuring any perturbations on the transiting planets orbital period (Miralda-Escudé 2002; Holman & Murray 2005; Agol et al. 2005; Heyl & Gladman 2007). The TTV technique is sensitive to Earth-sized planets (or smaller) when the perturber is in favourable orbital configurations – namely low-order mean motion resonances. The technology to take advantage of this technique already exists and in fact ground-based TTV experiments are the first to have probed for Earth-sized planets around main sequence stars (see for example, Holman et al. 2006; Steffen & Agol 2005).

The TTV method requires many light curves of high time-resolution coupled with precision photometry when searching for Earth-sized exoplanets. RISE (Rapid Imager to Search for Exoplanets) is a new instrument designed primarily for this purpose. It was designed and built by scientists from Queens University, Belfast, Liverpool JMU and the University of Manchester, and is mounted on the fully robotic 2-m Liverpool Telescope (LT) on La Palma. It was commissioned in late February 2008 and is described in Sect. 2.1.

In the months following the commissioning run some non-TTV targets were observed with RISE to test the instrument and reduction procedures further. These data have already been used to accurately characterise a recently discovered planet from the SuperWASP-N camera, WASP-14b (see Joshi et al. 2008, for details). In this paper we present a full transit of WASP-3 observed during this period, along with a recently obtained partial transit. WASP-3b was also discovered by the SuperWASP-N camera (see Pollacco et al. 2008) and was found to be a relatively massive planet closely orbiting an unevolved main sequence star of spectral type F7-8V.

However, there is currently only transit photometry available for WASP-3 from relatively small aperture telescopes (eg the IAC 80 cm and Keele 60 cm). In this paper we analyse the RISE light curves to provide improved model fits of the planetary parameters and also to demonstrate the potential timing accuracy obtainable from the ground using such an instrument. We are in the process of targeting several other planetary systems with RISE in order to detect TTV signals.

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[1] see http://exoplanet.eu/

In Sect. 2 we describe the RISE instrument and the observation and data reduction procedures. We describe the fitting technique used to extract the parameters and uncertainties from the light curves in Sect. 3, and finally in Sects. 4 and 5 we present, discuss and summarise our results.

2. Observations and data reduction

2.1. The RISE instrument

RISE was mounted on the LT and commissioned in February 2008, and was designed to obtain high time precision light curves of transiting extrasolar planets. Due to transiting systems often being relatively bright targets ($m_v < \sim 13$), overheads due to readout time adversely affect the timing precision we can obtain. Therefore, RISE consists of a thermoelectrically cooled frame transfer CCD (using an e2v CCD47-20 back illuminated chip) which allows exposure times as short as 1 s without dead time. For very bright targets (e.g. HD 189733, $V \sim < 8$) this allows much more data (>10 000 images) to be taken during a typical 2−3 h transit than from a traditional CCD with significant readout time.

The CCD has 1024×1024 13.0 μm pixels in the light sensitive region, giving a field of view of 9.4×9.4 arcmin squared. This relatively large field should provide many bright sources to be used as reference stars, therefore improving the potential photometric accuracy, and allows accurate light curves to be taken for relatively uncrowded fields previously unattainable with RATCAM – the other imager on the LT with a field of view of 4.6×4.6 arcmin squared.

Furthermore, the RISE instrument uses a single broadband filter composed of Schott KG5 and OG515, which results in a band pass of 500−700 nm. This allows the instrument to collect as many photons as possible during an exposure, which again should improve the photometric accuracy we can obtain and therefore the timing accuracy. For more information about the design and performance of RISE, and the LT, see Steele et al. (2008).

2.2. RISE photometry

A full transit of WASP-3 was observed using RISE on the night of 18 May 2008, and a partial transit was observed on the night of 4 September 2008, corresponding to epochs $E = 250$ and 309, respectively, from the ephemeris of Pollacco et al. (2008),

$$T_c = 2\,454\,143.8503 + 1.846834\,E \text{ [HJD].}$$

The data from 18 May consist of 4800×3 s exposures beginning at 23:15 UT spanning a 4 h period starting ~0.8 h before ingress and ending ~0.4 h after egress, resulting in an airmass range of ~1.99−1.02. The 4 September data consist of 3900×3 s exposures beginning at 22:30 UT, spanning 3.25 h starting approximately 0.7 h before ingress and ending just before egress – corresponding to an airmass range of ~1.08−2.10.

The detector was set to 2×2 binning mode for both transits giving a scale of 1.1 arcsec/pixel, and the LT was defocussed so that the chip was not saturated and well below the non-linearity regime resulting in a typical *FWHM* of ~3−4 pixels (3.3−4.4 arcsec). This also helps to minimise errors associated with flat fielding. Both nights were photometric.

The images were first de-biased and flat fielded with combined twilight flats using standard IRAF[2] routines. Aperture
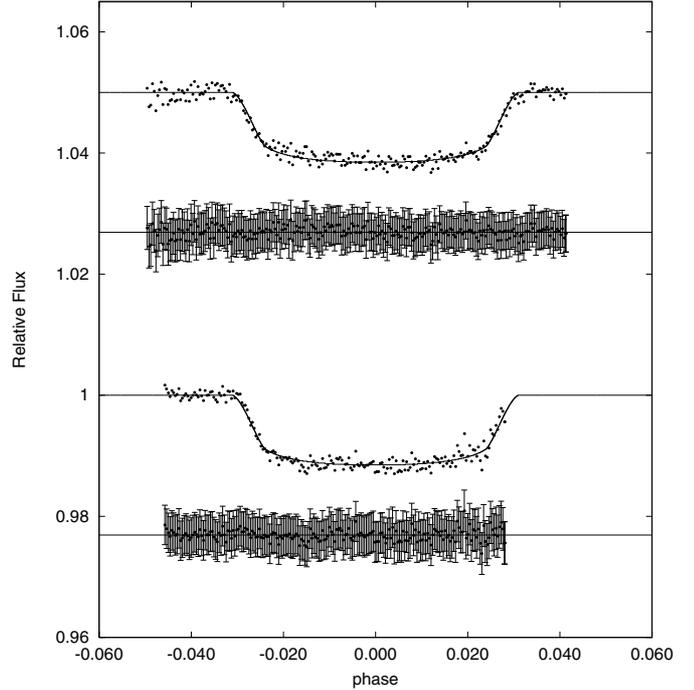

Fig. 1. RISE light curves of WASP-3 taken on 18 May 2008 (*upper*, offset by 0.05) and 4 Sep. 2008 (*lower*) shown in 1 min bins with the best fit model from the MCMC analysis overplotted. Residuals are shown offset along with their error bars after rescaling so $\chi^2_{red} = 1$ and to account for red noise.

photometry was then performed on the target star and 3 nearby companion stars using Pyraf[3] and the DAOPHOT package using a 7 pixel aperture (the same companion stars were not used in both cases due to different field orientations). The flux of WASP-3 was then divided by the sum of the companion stars (all checked to be non-variable) to obtain each light curve. Initial estimates of the photometric errors were calculated using the aperture electron flux, sky and read-noise. The light curves were then normalised by dividing through with a linear function of time fitted to the out-of-transit data, setting the unocculted flux of WASP-3 equal to 1, revealing a transit of depth ~1.17%. The light curves along with their best fit models and residuals are shown in Fig. 1, after grouping the data into 1 min bins. The rms of the residuals from the best fit model (see Sect. 3.1) are ~4.3 mmag for each light curve per 3 s exposure.

3. Results and analysis

3.1. Determination of system parameters

In order to determine the system parameters from the photometry, a parameterised model was constructed. This used Kepler's Laws and assumed a circular orbit to calculate the normalised separation (z) of the planet and star centres as a function of time from the stellar mass and radius ($M_\star$ and $R_\star$), the planetary mass and radius (M_p and R_p), the orbital period and inclination (P and i), and finally a central transit time for each light curve ($T_{0,n}$). The analytic models of Mandel & Agol (2002) were then used to calculate the stellar flux occulted by the planet from

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the normalised separation and the planet/star radius ratio (ρ) assuming the quadratic limb darkening function

$$\frac{I_\mu}{I} = 1 - a(1 - \mu) - b(1 - \mu)^2,$$

where I is the intensity, μ is the cosine of the angle between the line of sight and the normal to the stellar surface, and a and b are the linear and quadratic limb darkening coefficients, respectively.

The limb darkening parameters were obtained from the models of Claret (2000). We linearly interpolated the ATLAS tables for $T_{\rm eff}$ = 6400 K, $\log g$ = 4.25, [Fe/H] = 0.0 and v_t = 1.0 km s^{-1} (from Pollacco et al. 2008) to obtain limb darkening parameters in both the V and R bands. The average of the parameters from each of the bands was then taken to be our theoretical limb darkening parameters.

A Markov-Chain Monte Carlo (MCMC) algorithm was then used to obtain the best fit parameters and their uncertainties (see for example, Tegmark et al. 2004; Holman et al. 2006; Collier Cameron et al. 2007; Winn et al. 2008). This consists of calculating the χ^2 fitting statistic,

$$\chi^2 = \sum_{j=1}^{N} \frac{(f_{j,\rm obs} - f_{j,\rm calc})^2}{\sigma_j^2},$$

where $f_{j,\rm obs}$ is the flux observed at time j, σ_j is the corresponding uncertainty and $f_{j,\rm calc}$ is the flux calculated from the model for time j and for the set of physical parameters described above. The best fit parameters and uncertainties are then found by starting a long chain that explores the probability densities in parameter space by accepting or rejecting subsequent parameter sets based on the difference in χ^2. The new parameter set is accepted if χ^2 is lower than that of the previous set, or accepted with probability

$$P = \exp\left(\frac{-\Delta\chi^2}{2}\right)$$

if χ^2 is higher than that of the previous parameter set. New parameter sets are chosen by adding a small random amount to each of the previously accepted parameters determined by a jump function. These jump functions consist of a random value selected from a Gaussian distribution with mean 0 and standard deviation of 1, scaled by a factor associated with each parameter (which ideally should initially be set near to each parameter's 1σ uncertainty to speed chain convergence). These scale factors were then resized from their initial values so that ~25% of all new parameter sets were accepted. The reader is referred to the aforementioned literature for more details of MCMC fitting techniques.

To obtain reliable estimates of parameters and their uncertainties it is important that the photometric errors are calculated accurately. The photometric errors σ_j are first rescaled so that the best fitting model for each light curve has a reduced χ^2 ($\chi^2_{\rm red,n}$) of 1, which required the initial error estimates to be multiplied by the factors $\sqrt{\chi^2_{\rm red,1}}$ = 1.73 and $\sqrt{\chi^2_{\rm red,2}}$ = 2.04. This indicates that the photometric errors are considerably higher than what would be expected from photon noise alone.

It is also vital to account for any correlated ("red") noise in the data (see Pont et al. 2006; Gillon et al. 2006). Following Winn et al. (2008) we evaluated the presence of red noise in each light curve by calculating a factor β and again rescaling the σ_j in the χ^2 calculation by this value. A value for β is determined by

analysing the residuals from the best fit model of the light curves. Calcualting the standard deviation of the residuals σ_1 and also the standard deviation after binning the residuals into M bins of N points σ_N, one would expect

$$\sigma_N = \frac{\sigma_1}{\sqrt{N}}\sqrt{\frac{M}{M-1}}$$

in the absence of red noise. However, this is usually larger by a factor β. As pointed out in Winn et al. (2008), β only depends weakly on the averaging time, therefore we used the average of β values calculated from a range of averaging times from 10−30 min to rescale the photometric errors. The values of β used were 1.43 and 1.35 for the full transit and partial transit, respectively.

To account for any normalisation errors in the light curves, a further 2 free parameters were added for each transit. These were the out-of-transit flux ($f_{\rm oot,n}$) and a time gradient ($t_{\rm Grad,n}$), which are vital for TTV measurements as these effect the symmetry of the light curve and therefore the central transit times. An airmass correction k was tried for the full transit instead of the time gradient by multiplying each point by a factor $\exp(-kz)$ where z is the airmass. This was found to cause an insignificant change in the output parameters and so the time gradient was used in our final analysis. The chains would not converge when an airmass correction was used instead of a time gradient for the partial transit.

A Gaussian prior was added to the χ^2 fitting statistic so that

$$\chi^2 = \sum_{j=1}^{N} \frac{(f_{j,\rm obs} - f_{j,\rm calc})^2}{\sigma_j^2} + \frac{(M_{\star,j} - M_0)^2}{\sigma_M^2},$$

where $M_{\star,j}$ is the mass of the star used to calculate each model at time j, and M_0 and σ_M are the stellar mass and corresponding uncertainty as given in Pollacco et al. (2008). This is so the error in the stellar mass is taken into account when determining parameters from the MCMC probability distributions. The stellar radius cannot be allowed to vary independently of the stellar mass as the chains will not converge. Therefore, the stellar radius was updated for each choice of $M_\star$ using the scaling relation $R_\star \propto M_\star^{1/3}$, whilst P and M_p were held fixed at their previously determined values, as their uncertainties do not have any significant effect on the output probability distributions.

An initial MCMC analysis was used to estimate the initial parameters and jump functions for ρ, i, $T_{0,n}$, $f_{\rm oot,n}$ and $t_{\rm Grad,n}$. Five separate chains with 100 000 points were then computed with the initial free parameters set by adding a 5σ Gaussian random to their previously determined best fit values. The first 20% of each chain was eliminated to keep the initial conditions from influencing the results, and the remaining part of the chains were merged to obtain the best fit parameters and uncertainties. These were not assumed to be Gaussian and were obtained by setting the best fit value to the modal value of the probability distribution, and the 1σ lower (upper) limit as the value where the integral of the distribution from the minimum (maximum) value to it was equal to 0.159. To test that the chains had all converged to the same parameter space, the Gelman & Rubin statistic was then calculated for each of the free parameters (this time assuming Gaussian errors) (Gelman & Rubin 1992). It was found to be less than 0.5% from unity for all parameters, a good sign of mixing and convergence. The transit duration ($T_{\rm d}$) and impact parameter (b) were also calculated for each parameter set in the chain using the equations of Seager & Mallén-Ornelas (2003), and were treated the same as the fitted parameters to determine

Table 1. Parameters and 1σ uncertainties for WASP-3b as derived from MCMC fitting and some further calculated parameters.

Parameter	Symbol	Value	Units
Planet/Star radius ratio	ρ	$0.1014^{+0.0010}_{-0.0008}$	
Orbital inclination	i	$85.06^{+0.16}_{-0.15}$	deg
Impact parameter	b	$0.448^{+0.014}_{-0.014}$	
Transit duration	T_d	$2.753^{+0.020}_{-0.013}$	h
Transit epoch	T_0	$2\,454\,605.55915 \pm 0.00023$	HJD
Period	P	1.846835 ± 0.000002	days
Planet radius	R_p	$1.29^{+0.05}_{-0.12}$	R_J
Planet mass[a]	M_p	$1.76^{+0.08}_{-0.14}$	M_J
Planet density	ρ_p	$0.82^{+0.14}_{-0.09}$	ρ_J
Planetary surface gravity	$\log g_p$	$3.42^{+0.06}_{-0.04}$	[cgs]

[a] From Pollacco et al. (2008), displayed here for convenience.

Table 2. Central transit times and uncertainties for the RISE photometry.

Epoch	Transit time [HJD]	Uncertainty (days)
0	$2\,454\,605.55956$	0.00035
59	$2\,454\,714.52210$	0.00036

best fit values and uncertainties. This was to account for any correlated errors.

To check for any errors that may have resulted from a poor choice of limb darkening parameters, the above procedure was repeated, this time allowing the linear limb darkening parameter (a) to vary freely whilst holding the quadratic limb darkening parameter (b) fixed at the theoretical value obtained from the models of Claret (2000). This is the same procedure used by Winn et al. (2008), and did not cause any significant changes to the best fit values; however, it did increase the errors in i and ρ slightly and hence these results were adopted as our final values. A further check on the choice of limb darkening parameters involved repeating this process by replacing the quadratic limb darkening coefficient (b) determined for the combined $V+R$ filter by those obtained for the individual V and R filters. This caused no significant variation from the previously determined results in either case, and thus we conclude that the choice of limb darkening parameters had no detrimental effects on our results. This was not surprising, as the linear limb darkening parameter was much more sensitive to the choice of filter than the quadratic parameter.

4. Results

4.1. MCMC results

The parameters and their uncertainties calculated from the MCMC fit are shown in Table 1. The planet radius was found to be $1.29^{+0.05}_{-0.12}$ R_J, and the planet density $0.82^{+0.14}_{-0.09}$ ρ_J – consistent with that of the discovery paper. Therefore the derived planetary parameters are still in agreement with models of highly irradiated Hot Jupiters (e.g. Fortney et al. 2007) as concluded in Pollacco et al. (2008).

The inclination is also consistent with that calculated previously but it is now known much more accurately with a value of $85.06^{+0.16}_{-0.15}$ deg – a factor of ~5 increase in precision. However, the transit duration was found to be inconsistent with that of the
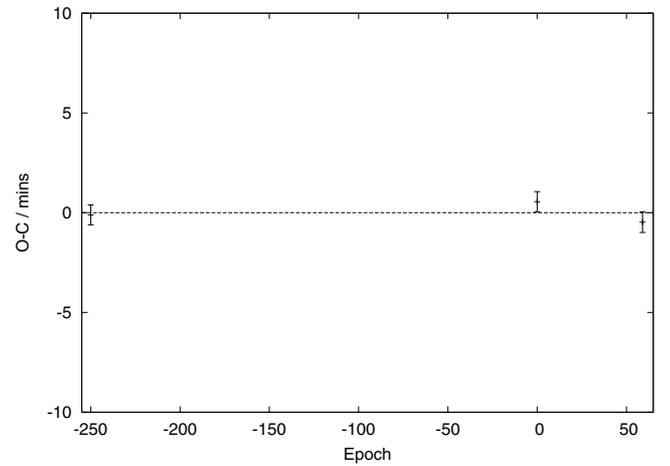
Fig. 2. Timing residuals of the RISE transits of WASP-3 and the epoch given in Pollacco et al. (2008) using the updated ephemeris.

discovery paper (~4.1σ). T_d is very sensitive to the inclination of the system, and we believe the discrepancy arises due to the discovery data not being of sufficient quality to constrain it accurately, and therefore has resulted in an underestimated error in the transit duration. If the updated inclination from the RISE data is used along with the remaining parameters from Pollacco et al. (2008), then the calculated T_d is found to be consistent with our value.

4.2. Transit ephemeris

The RISE transits do not differ significantly from the discovery ephemeris; however, this can be updated using the longer baseline. This was found by minimizing χ^2 by fitting a linear function of Epoch E and period P to the transit times from this paper (shown in Table 2) and the ephemeris of Pollacco et al. (2008),

$$T_c(E) = T_c(0) + EP,$$

where $T_c(0)$ was set to the central transit time from 18 May 2008 RISE data. The results were $T_c(0) = 2\,454\,605.55915 \pm 0.00023$ [HJD] and $P = 1.846835 \pm 0.000002$ days. Figure 2 shows a plot of the timing residuals of WASP-3 transits using the updated ephemeris.

5. Summary and discussion

We have presented some of the first results from RISE of a full and partial transit of the exoplanet system WASP-3. An MCMC analysis was used to update the parameters which were found to be consistent with those of Pollacco et al. (2008), except for the calculated value for the transit duration, which is explained in terms of the large uncertainty in the previously determined inclination. Using the central transit times an updated ephemeris was calculated to aid in further observations of this system.

Although the timing accuracy was not of the order we intended for RISE ($< \sim 10\,\mathrm{s}$), other transits observed with RISE (for TTV experiments) are producing much more impressive light curves (see Steele et al. 2008). This is mainly because the photometric errors for each WASP-3 light curve had to be multiplied by the factors $\sqrt{\chi^2_{\mathrm{red}}} = 1.73$ and 2.04 in our analysis so that the reduced $\chi^2 = 1$. It is as yet unclear why this is the case, but is perhaps due to randomised systematics caused by a combination of the moon, changing flat-field structure and poor autoguiding. Further RISE observations currently being made at the LT should not suffer from these problems, and we hope to report on further transit timing datasets in future papers.

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