An Analysis of Transiting Hot Jupiters Observed with K2: WASP-55b and WASP-75b

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Abstract

We present our analysis of the K2 short-cadence data of two previously known hot Jupiter exoplanets: WASP-55b and WASP-75b. The high precision of the K2 light curves enabled us to search for transit timing and duration variations, rotational modulation, starspots, phase-curve variations and additional transiting planets. We identified stellar variability in the WASP-75 light curve which may be an indication of rotational modulation, with an estimated period of $11.2 \pm 1.5$ days. We combined this with the spectroscopically measured $v \sin i$ to calculate a possible line of sight projected inclination angle of $i_L = 41^\circ \pm 16^\circ$. We also perform a global analysis of K2 and previously published data to refine the system parameters.

Key words: planets and satellites: individual (WASP-75b, WASP-55b) – stars: individual: (WASP-75, WASP-55, EPIC 206154641, EPIC 212300977)

Online material: color figures

1. Introduction

The K2 mission has been in operation since 2014 May following the failure of two reaction wheels in the original Kepler mission (Howell et al. 2014), monitoring fields along the ecliptic plane. The spacecraft experiences a roll which introduces systematics in the photometric light curves on a timescale of approximately 6 hr when it is corrected by a thruster event. As a result the quality of the photometry can be degraded by up to a factor of 4 (Howell et al. 2014). Despite this, methods such as self flat-fielding (SFF) (Vanderburg & Johnson 2014), K2SC (Aigrain et al. 2016) and routines that we have built (Močnik et al. 2016) can reduce this effect to the extent that the quality of the produced data is near that of the original mission.

Following the initial discovery of an exoplanet, subsequent observations are common if a planet possesses unique characteristics (e.g., WASP-18b—Hellier et al. 2009). They are also frequent if the system is readily observable from Earth; for example, those with a bright host star such as WASP-33b (Christian et al. 2006) or planets with a large transit depth such as WASP-43b (Hellier et al. 2011). For other planets however, follow-up observations can range from infrequent to absent, meaning we can miss crucial discoveries about these systems. An example of this are the recent K2 observations of the WASP-47 system that revealed two additional companions (Becker et al. 2015). WASP-55b and particularly WASP-75b are examples of two planets that have had little follow-up since their initial discoveries.

WASP-55b was found to be a moderately inflated hot Jupiter with a mass of $0.57 \pm 0.04 M_{\text{Jup}}$ and a radius of $1.30 \pm 0.05 R_{\text{Jup}}$ orbiting a G1 star discovered in 2011 (Hellier et al. 2012). WASP-75b was discovered by Gómez Maqueo Chew et al. (2013) as a hot Jupiter with a mass of $1.07 \pm 0.05 M_{\text{Jup}}$ and a radius of $1.27 \pm 0.05 R_{\text{Jup}}$. It orbits WASP 75, a F9 star with an orbital period of 2484 days. In this paper we present a refined set of system parameters for WASP-55b and WASP-75b. We also search the K2 light curves for transit timing and duration variations, stellar rotational modulation, starspot occultations, phase-curve variations and search the residual light curves for additional transiting companions.

2. K2 Data Reduction

2.1. Data Extraction

WASP-55b (EPIC 212300977) was observed during campaign 6 of the K2 mission, which ran from 2015 July 14 until 2015 September 30. It produced a total of 112,672 short-cadence images. WASP-75b (EPIC 206154641) was observed during campaign 3, it produced 101,370 short-cadence images between 2014 November 14 and 2015 February 3. We retrieved the target pixel files for each system using the Barbara A. Mikulski Archive for Space Telescopes (MAST\textsuperscript{3}).

The large motion of the point-spread function (PSF) on the detector in campaign 3 was cause for concern when reducing the raw images. A traditional fixed-mask method used

\textsuperscript{3} https://archive.stsci.edu/k2/
by a majority of the K2 data reduction to date (e.g., Močnik et al. 2016) appeared to degrade the precision of the output light curves. To resolve this issue, we used an aperture photometry routine written using PYRAF, with aperture sizes ranging from 0.5 to 8.5 pixels in steps of 0.25 pixels that used a flux-weighted centroid method to re-position the aperture based upon the PSF position in each frame. For the WASP-75b data set an aperture size of 6.5 pixels led to a reduction in the rms from 368 PPM to 325 PPM and for WASP-55b, a 5.5 pixel aperture reduced the scatter from 568 PPM to 530 PPM.

2.2. De-trending

As noted in Section 1, K2 light curves contain systematics that correlate with position of stellar flux on the detector. This is visibly seen as a sawtooth-like pattern in the light curve, which can be observed in Figure 1. We were able to correct for a majority of these systematics using the methods of Močnik et al. (2016). However, for WASP-75b there were areas of strong systematics caused by a high spacecraft jitter, that were not corrected well by this method. The systematics correlated heavily with the X and Y position of the PSF on the detector, with large jumps in position and flux at every thruster event. We used a moving gradient to detect the areas with jumps and used these dates as boundaries between windows over which to correct the systematics, rather than a fixed window size. With this method, a third order polynomial fit to the flux versus arclength trend was enough to successfully remove the visible trends (Figure 1).

To model the low-frequency variability from the light curve of WASP-75b we used a Gaussian convolution method, similar to that of (Močnik et al. 2016) but with a kernel size larger than the timescales of systematic noise and transit events. This was then removed from the light curve before further analysis. We also performed a running median filter, with a kernel size of 21 points, to clip all data that were greater than 8-σ from the median-filtered residuals. In total, we clipped 2409 and 4905 points from the WASP-55b and WASP-75b light curves, respectively. The de-trended light curves are shown in Figure 2.

3. System Parameters

To determine the parameters of the system, we used an adaptive Markov chain Monte Carlo (MCMC) routine (Collier Cameron et al. 2007; Pollacco et al. 2008; Anderson et al. 2015) to simultaneously analyze the K2 light curves with their respective previously published radial velocity (RV) data.

For WASP-55b and WASP-75b, we used the normalized K2 light curves with the CORALIE RVs from Hellier et al. (2012) and Gómez Maqueo Chew et al. (2013), respectively. We assumed that the orbit was circular for the main MCMC runs, but set eccentricity as a free parameter on subsequent runs to place a constraint on its upper limit for both systems. We performed an additional run using the ground-based transit light curves from Hellier et al. (2012) for WASP-55b and Gómez Maqueo Chew et al. (2013) for WASP-75b to refine the ephemeris of both planets by extending the baseline. We present the updated system parameters in Tables 1 and 2 and the phase-folded light curves and models in Figures 3 and 4.

We used a four-parameter law to determine the limb darkening coefficients with values interpolated from those of Sing (2010) and based upon stellar temperature. We found that, for both systems, the stellar effective temperatures produced limb darkening coefficients that were in good agreement with the shape of the light curve. There were no visible anomalies in the residuals (see the middle panel in Figures 3 and 4) as has been the case for some planets that we have studied (e.g., Močnik et al. 2017).

We obtained our values of the stellar mass from a comparison with stellar models by using the BAGEMASS code of Maxted et al. (2015). This took as inputs, the spectroscopic values of stellar effective temperature and metallicity (\(T_\text{eff} = 6500 \text{ K}\)) as well as stellar density from initial MCMC runs. We used the calculated values as a prior constraint in our global MCMC.

Evans et al. (2016) discovered a faint, nearby companion to WASP-55b. They determined that it had a magnitude difference of 5.210 ± 0.018 in the r\(_\text{TCI}\) band at a distance of 4.345 ± 0.010, placing it within our aperture. We used Equation (3) of Daemgen et al. (2009) to correct our light curve for the additional flux measured from the companion star. The result was a minor difference in the calculated eclipse.
We find a new value of 0.01551 \(\pm\) 0.00005 compared to 0.01550 \(\pm\) 0.00004 before the correction.

4. No Transit Duration or Timing Variations

Additional planetary companions can cause variations in the timing of transit events due to the gravitational perturbations that they cause (Agol et al. 2005; Holman & Murray 2005). We searched for transit timing variations (TTVs) and Transit duration variations (TDVs) in the WASP-55b and WASP-75b data sets by splitting the light curves at midpoints between each transit. We then performed a single MCMC run for each transit, with no other input data. We used the parameters from the global MCMC run as prior constraints, with transit epoch and duration set as free parameters.

Against the null hypothesis of equally spaced and equal duration transit events, for WASP-55b we found a \(\chi^2\) of 28.7 and 6.3 for the TTVs and TDVs, respectively, with 17 degrees of freedom. We place upper limits on the TTVs of 25s and 100s for the TDVs. For WASP-75b, the measured TTVs and TDVs had a \(\chi^2\) of 24.8 and 36.3, with 28 degrees of freedom. The upper limits for the TTVs and TDVs were 35 s and 120 s, respectively. Given the lack of significant TTVs and TDVs, we can rule out the existence of large, close-in companion planets for both systems.

5. No Starspot Occultations but Stellar Variation in WASP-75

We performed a thorough visual inspection for starspots in both the de-trended light curves and model-subtracted residuals but we found no evidence of starspot occultations in either the WASP-55b or WASP-75b data.

We find no variations in the WASP-55b light curve but do detect low-frequency variations in the WASP-75b light curve. To investigate these, we used K2SC (Aigrain et al. 2016) to obtain a systematic-corrected light curve from the pre-search conditioned K2 data, which included low-frequency variations but excluded transit events (Figure 5). We used this method as our low-frequency variation light curve included a long-term trend that was removed well by the pre-search data conditioning module. We used the autocorrelation function (ACF) of McQuillan et al. (2013) and a Lomb–Scargle (LS) periodogram to search the light curve for rotational modulation. From the ACF, we found a period of 11.7 \(\pm\) 0.5 days determined from the first three peaks, that is possibly indicative of rotational modulation. This is in agreement with the value of 11.2 \(\pm\) 1.5 produced by the LS-periodogram.

For WASP-75b, we calculated an updated value for macroturbulence \((v_{\text{mac}})\) of 4.05 \(\pm\) 0.41 km s\(^{-1}\) using the calibrations of Doyle et al. (2014) and produced a new value of \(v\sin(i)\) = 3.8 \(\pm\) 1.0 km s\(^{-1}\). Assuming spin–orbit...
alignment, this implies a stellar rotation period of 16.9 ± 4.5 days. The marginal agreement between the predicted and measured values of stellar rotation could hint at the possibility of a non-aligned stellar inclination angle. We used the new \( v \sin(i) \) with the more conservative LS-periodogram measurement of the rotation period of the star to determine that WASP-75b has a possible rotation speed of \( v = 5.7 \pm 0.8 \) km s\(^{-1}\) and stellar line-of-sight inclination angle of \( i = 41^\circ \pm 16^\circ \). If we assumed Sun-like starspot latitudes and differential rotation, the stellar line-of-sight inclination angle would be \( i = 39^\circ \pm 14^\circ \).

It is possible to use the value of \( i \) with the obliquity angle, that can be measured using the Rossiter–McLaughlin (RM) effect (McLaughlin 1924; Rossiter 1924; Triaud 2017), to calculate the true angle (Ψ) between the stellar rotation and orbital axes. Ψ is important in theories of the formation and evolution of planetary systems (Campante et al. 2016). A RM measurement of WASP-75b would therefore be beneficial in this case. We estimated the amplitude of the RM effect to be 13 ± 3 m s\(^{-1}\) for WASP-75b. This effect should be measurable with high-resolution spectrographs and we predict a typical RV precision of ∼4 m s\(^{-1}\) from a 900 s HARPS spectrum of WASP-75.

### 6. No Phase-curve Variations

At optical wavelengths, phase-curve variations are expected to comprise of four main constituents: ellipsoidal variations (Welsh et al. 2010; Jackson et al. 2012), Doppler beaming (Groot 2012), a component of reflected light from the star (Madhusudhan & Burrows 2012) and a secondary eclipse
Table 2
In the Same Way as Table 1, we show the Orbital, Stellar, and Planetary Parameters from the MCMC Analysis of WASP-75b (EPIC 206154641), Listing Each of the Proposal, Derived and Parameters Controlled by Priors, Separately

| Symbol | This Work | Gómez Maqueo Chew et al. (2013) |
|--------|-----------|---------------------------------|
|        | (unit)    |                                  |
| M_p (M_J) | 1.16 ± 0.03 | 1.14 ± 0.07                     |
| T eff (K) | 6035 ± 48 | 6100 ± 100                      |
| Fe/H   | 0.07 ± 0.09 | 0.07 ± 0.09                     |

MCMC proposal parameters

| P (days) | 2.4842014 ± 0.0000004 | 2.484193 ± 0.000003 |
| T_e (days) | 7009.94594 ± 0.00002 | 6016.2669 ± 0.0003 |
| R_p/R_s | 0.08097 ± 0.00008 | 0.0822 ± 0.0011 |
| R_p/R_s^* | 0.01133 ± 0.00005 | 0.0107 ± 0.0003 |
| b       | 0.8926 ± 0.0007 | 0.8825 ± 0.0068 |
| K_i (m s^{-1}) | 145 ± 4 | 146 ± 4 |
| γ (m s^{-1}) | 2264 ± 3 | 2264.29 ± 0.06 |

MCMC proposal parameters constrained by priors

| M_p (M_J) | 1.08 ± 0.05 | 1.07 ± 0.05 |
| R_p (R_J) | 1.31 ± 0.02 | 1.270 ± 0.048 |
| log(R_e/R_p) | 3.16 ± 0.01 | 3.179 ± 0.031 |
| log(R_e/R_p^*) | 0.48 ± 0.02 | 0.521 ± 0.058 |
| T eff (K) | 1688.25 ± 0.46 | 1710 ± 20 |

Note. We again tabulate our results and those provided by the literature.

* Assuming a zero bond albedo and efficient day–night redistribution of heat.

(Esteves et al. 2013). Using equations from Mazeh & Faigler (2010) and the system parameters in Tables 1 and 2 we calculated the predicted amplitudes of these effects and created a phase-curve for each of the two systems. We calculated predicted values of the ellipsoidal variations, Doppler beaming, reflection and secondary eclipse depth as 0.4, 0.9 and 13 PPM for WASP-55b and 3.4, 1.9 and 26 PPM for WASP-75b.

We used a Levenberg–Marquardt algorithm to attempt to fit the above model to the phase-folded residual light curve of each system. However, in both cases, we found a negligible amplitude provided the best fit, which was also confirmed visually. We therefore did not detect any phase variations in either system. The predicted values are lower than the precision of the light curves; even if variation of this magnitude were to exist, we would not be able to detect them with the current data. It is possible that the de-trending methods used could have removed phase variations from the original data, but signal injection tests performed by Močnik et al. (2017) have shown that the SFF method should preserve periodic variations. We therefore placed conservative estimates on the upper limits of the phase curve variations and secondary eclipse depths of 100 PPM for WASP-55b and 60 PPM for WASP-75b. As a result, we have placed upper limits on the geometric albedos of 0.8 and 0.2 for WASP-55b and WASP-75b, respectively. We plot the phase-folded, binned residual light curves in Figure 6 along with the predicted and lower-limit phase-curve models.
7. No Additional Transiting Planets

To search for signals of additional transiting planets we used the box-least-squares method of Collier Cameron et al. (2006) on the model-subtracted residuals for each planet. We found no significant signals in the residuals of WASP-55b data set, but did find significant peaks in the periodogram of WASP-75. However, further inspection revealed that this was due to the presence of residual correlated noise. We therefore found no signals from additional transiting planets with periods between 0.5 and 35 days in either the WASP-55b or WASP-75b data and we placed upper limits on the eclipse depths of additional planets to 280 and 190 PPM at a period of 0.5 days.
8. Conclusions

In this paper, we have used K2 data, taken during campaigns 3 and 6, to produce and analyze light curves for the WASP-75b and WASP-55b systems, respectively. We have refined the orbital parameters of both systems, as the high-quality light curves allowed us to model the transit with a much greater precision than is possible from ground-based observations.

Generally, the refined parameters agreed well with the previously published results and we found no major discrepancies between the different sets of data for each planet. For WASP-55b the parameters produced by this work, shown in Table 1, agreed very well with those of Southworth et al. (2016). We found minor differences between the results and those of Hellier et al. (2012) that have arisen as we used the stellar metallicity from Mortier et al. (2013) rather than CORALIE spectra and we used a different method to estimate the stellar mass.

For the WASP-75b data set there were minor differences between the values of orbital period, transit depth, transit duration, and the impact parameter that we derived and those of Hellier et al. (2012) that occur as we are able to better constrain the shape of the transit with higher quality data.

We found no evidence of transit timing or duration variations in both systems, and placed upper limits of 25 s and 35 s for TTVs and 100 s and 120 s for TDVs for WASP-55b and WASP-75b, respectively. There was no evidence of starspot occultations in either system, but we did find low-frequency variation in WASP-75b. From this, we have tentatively estimated its rotation period as 11.24 ± 1.54 days and calculated an estimate of the stellar line-of-sight inclination angle of $i_\sigma = 41^\circ \pm 16^\circ$. We also found no evidence of phase curve variations or additional transiting planets in either system.

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