Light Curve Analysis for The Transit of Exoplanet WASP-74b Observed at Bosscha Observatory

R. W. Wibowo1,2, M. Yusuf1, T. Hidayat2, P. Mahasena1,2, D. Mandey1,2, B. Dermawan2
1Bosscha Observatory, Institut Teknologi Bandung, Jalan Peneropong Bintang, Lembang, Bandung Barat 40391, Indonesia
2Astronomy Study Program, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
E-mail: ridlo.w.wibowo@gmail.com

Abstract. WASP-74b is an exoplanet in one of the brighter systems accessible to Southern telescope. We report the analysis of light curve from the transit event of WASP-74b observed at Bosscha Observatory. This report is focused on deriving physical parameters from a single transit lightcurve of WASP-74b at around JD 2457597.14 using Markov Chain Monte Carlo sampler (MCMC) and simple trends model. Physical parameters of the system are successfully derived, in agreement with the discovery paper which uses data from longer monitoring and more thorough observation.

1. Introduction
There are several methods to detect exoplanet. The simplest and most widely used is transit method. Transit happens when an exoplanet moves in front of a host star. During the transit, the brightness of the host star will decrease. Although this dimming is very small, it is feasible to measure it using small telescope and inexpensive CCD. Finding new exoplanet with transit method will be one of the main research at the new national observatory that is planned to be built at Timau, East Nusa Tenggara (see Hidayat, T. et al., 2012).

WASP-74 is a slightly evolved F9 star with mass of 1.48 ± 0.12 M⊙ and radius 1.64 ± 0.05 R⊙. It is a star of V=9.7 located at RA = 20h18m09.32s and declination=−01°04′32″ (J2000). First detection of exoplanet WASP-74b was carried out using WASP-South survey telescope. It is a 0.95 MJup planet with a radius of 1.5 RJup orbiting the host star with period around 2 days. More detail on this system can be found on the discovery paper (Hellier et al., 2015).

In this paper, we present the light curve from the transit event of WASP-74b observed at Bosscha Observatory. It is important to point out that this paper will focus on the analysis of a single light curve to derive physical parameters using Bayesian approach (MCMC method).

2. Data and Analysis
2.1. Observation
WASP-74b was observed at Bosscha observatory by M. Yusuf using Planewave CDK telescope (14", f/7.2), with CCD detector FLI Proline 11002 in R filter. The observations were carried out for two nights (July 27th and 29th 2016). Due to bad weather conditions however, reliable
data used in this analysis is only from observation on July 27th, 2016. Differential photometry was carried out with total length of observation about 4.7 hours and a cadence of $\sim 1.4$ minutes.

2.2. Light Curve Analysis

Figure 1 presents the light curve extracted from our observation. We subjectively remove some bad data points with large errorbar which we suspect due to thin cloud during observation. The removed points can be seen as gap around JD 2457597.08. This light curve may still contain contamination from some correlated (red) noise, e.g. from instruments, astrophysical source, and airmass. This red noise can be removed if we have a good model of the noise source. In many cases, the modelling is difficult to be performed. We follow the method used in Exoplanet Transit Database (ETD, http://var2.astro.cz/ETD/) to simplify the red noise model for a single transit lightcurve. We add ‘quadratic’ trend to the model of the light curve,

$$\Delta m(t_i) = A - 2.5 \log F(\theta) + B(t_i - \bar{t}) + C(t_i - \bar{t})^2$$

We use transit model $F(\theta)$–with $\theta$ as parameter vector–from Mandel & Agol (2002). Detail of the transit model can be seen in this paper. We use the implementation of this model in PyTransit (Parviainen, 2015). Variable $A$ in Equation 1 represent the zero-point shift of the magnitudes, while $B$ and $C$ describe systematic trends in the data. Linear and quadratic terms are computed with respect to the mean time of observations $\bar{t} = \sum t_i / N$ to supress numeric errors.

Instead of using Lavenberg-Marquardt non-linear least squares for fitting procedure as in ETD, we use MCMC sampling to obtain marginal posterior density estimates for the model parameters. The joint model has 11 free parameters in total, all listed in Table 1, along with their priors. The limb darkening uses parameterisation as suggested in Kipping (2013). This parameterization allows us to use uniform priors from 0 to 1 to cover the whole physically sensible
limb darkening coefficients \((u, v)\)-space. We assume the data contains normally distributed white noise only. Therefore, we employ simple normal likelihood without taken error of the data into account to reduce computing time.

![Figure 2](image)

**Figure 2.** Marginal distributions and covariances for 11 parameters in unconstrained model (free all the parameters). Histogram from the left to the right are for each parameter: transit center, period, area ratio, star density, impact parameter, white noise, limb darkening parameter 1, 2, detrending constant A, B, and C.

We sample the posterior distribution with *emcee* package (Foreman-Mackey et al., 2013), a Python implementation of the Affine Invariant MCMC sampler (Goodman & Weare, 2010). To reduce burn-in time, we initialize the *emcee* sampler (walkers) using the parameter vector population found with PyDE, an implementation of the differential evolution global optimization algorithm (Storn & Price, 1997). We complete the analysis using NumPy, matplotlib (Hunter, 2007), and *corner.py* (Foreman-Mackey, 2016).

The posterior sampling is carried out by running the *emcee* sampler with 100 simultaneous chains (walkers) for 10000 markov chain steps. After burn-in period of 2000 steps and a thinning
Figure 3. Marginal distributions and covariances for 7 parameters in constrained model (period, limb darkening constants, and detrending constant C are fixed). Correlation between impact parameter $b$ and area ratio $k^2$, also anticorrelation between $b$ and star density $\rho_\star$ more clearly seen in this constrained model. We can also see anticorrelation between detrending constant $B$ and transit center $t_c$. 

factor of 281 based on the chain autocorrelation length estimates, we obtain 2900 independent posterior samples. Afterwards, we constrain our model with a fixed value for 4 parameters: period ($P$), limb darkening coefficients ($u$, $v$), and quadratic detrending term $C$. Thinning factor in constrained model is 84, resulting 9600 independent posterior samples.

We fix the period in constrained model, since the data is for a single transit event only. In many cases, when more than one transits are observed, the period can be obtained by folding and binning the light curve. Limb darkening constants ($u$, $v$) are fixed because their value are not so sensitive to the fitting result of our data (indicated by nearly uniform posterior as seen in Figure 2). We also remove quadratic term ($C$) in constrained model, since adding it as free
3. Result and Discussion

We list the model parameters for both unconstrained and constrained model in Table 1. The values correspond to the posterior medians (values) and the 16th and 84th percentiles (errors), closely correspond to the posterior mean $\pm 1\sigma$ estimates (if the posteriors are close to normal). We present the marginal distributions for all parameters in Figure 2 and Figure 3 which correspond to unconstrained and constrained model respectively. We also plot the data and best-fit of unconstrained model in Figure 1.

| Parameters                      | Prior               | Free all params       | Constrained        |
|---------------------------------|---------------------|-----------------------|--------------------|
| Transit center ($t_c$)          | $\mathcal{N}(2457597.13, 0.03)\pm 0.0012$ | $2457597.1376^{+0.0016}_{-0.0017}$ | $2457597.1376^{+0.0016}_{-0.0016}$ |
| Period ($P$)                    | $\mathcal{N}(2.13775, 0.02)\pm 0.0009$ | $2.1381^{+0.0012}_{-0.0012}$         | $2.13775$ (fixed) |
| Area ratio ($k^2$)              | $\mathcal{J}(0.007, 0.0125)\pm 0.0009$ | $0.0091^{+0.0012}_{-0.0012}$         | $0.0090^{+0.0009}_{-0.0009}$         |
| Stellar density ($\rho_*$)      | $\mathcal{N}(0.5, 0.05)\pm 0.0074$ | $0.5044^{+0.0048}_{-0.0048}$         | $0.5035^{+0.0051}_{-0.0051}$         |
| Impact parameter ($b$)          | $\mathcal{U}(0.99, 0.002)\pm 0.0002$ | $0.8410^{+0.0028}_{-0.0028}$         | $0.8428^{+0.0033}_{-0.0033}$         |
| White noise std ($\sigma$)      | $\mathcal{U}(0.002, 0.002)\pm 0.0002$ | $0.0033^{+0.0002}_{-0.0002}$         | $0.0033^{+0.0002}_{-0.0002}$         |
| Limb darkening par. ($q_1$)     | $\mathcal{U}(0.0, 0.1)\pm 0.0002$      | $0.5086^{+0.0326}_{-0.0326}$         | $0.49$ (fixed) |
| Limb darkening par. ($q_2$)     | $\mathcal{U}(0.0, 0.1)\pm 0.0002$      | $0.4719^{+0.0309}_{-0.0309}$         | $0.36$ (fixed) |
| Detrending constant $A$         | $\mathcal{U}(-1.53, -0.53)\pm 0.0004$ | $-1.0316^{+0.0004}_{-0.0004}$        | $-1.0316^{+0.0004}_{-0.0004}$        |
| Detrending constant $B$         | $\mathcal{U}(-0.02, 0.02)\pm 0.0005$  | $0.0076^{+0.0005}_{-0.0005}$         | $0.0074^{+0.0004}_{-0.0004}$         |
| Detrending constant $C$         | $\mathcal{U}(-0.005, 0.005)\pm 0.0002$ | $0.0001^{+0.0003}_{-0.0003}$         | $0.0$ (fixed) |

Derived parameters

| Radius ratio ($k = R_p/R_*$)     | $0.0953^{+0.0006}_{-0.0004}$ | $0.0951^{+0.0045}_{-0.0044}$        |
| Scaled semimajor axis ($a/R_*$) | $4.9564^{+0.1015}_{-0.1684}$ | $4.9546^{+0.1593}_{-0.1622}$        |
| Scaled semimajor axis ($a/R_*$) | $8.024^{+0.50}_{-0.57}$      | $8.020^{+0.53}_{-0.54}$             |
| Limb darkening coef. ($u$)      | $0.5876^{+0.75}_{-0.40}$     | $0.5$ (fixed)                        |
| Limb darkening coef. ($v$)      | $0.0328^{+0.0309}_{-0.0420}$ | $0.2$ (fixed)                        |

The computation cost of this fitting method largely depends on the number of walkers and MC steps. It is however rather cheap for a single transit with a simple model like presented in this work. It only takes several minutes in standard laptop for a single run. We compare our result with the discovery paper in Table 2, we can see that the sigma of our result are larger.

True physical parameters of the planet can not be derived by using transit data only. Therefore, we present the result in the form of ratios between parameters. It is possible to get true physical parameters by combining our result with other independent measurement such as radial-velocity (RV) or spectral observation of the host star (and isochrone fitting). For example, if we know the mass of the host star is $1.48 \pm 0.12 \, M_\odot$ (Hellier et al., 2015), the radius of the planet derived from our data is $1.53 \pm 0.12 \, R_{Jup}$ (still within $1\sigma$ from their result,
Table 2. Some of the parameters can be compared with the discovery paper Hellier et al., (2015). We must aware that the model used in here are different, so the direct comparison like this should be treated wisely.

| Parameters             | Our result          | Hellier et al., (2015) |
|------------------------|---------------------|------------------------|
| Period (days)          | $2.1381^{+0.0193}_{-0.0202}$ | $2.137750 \pm 0.000001$ |
| Area ratio             | $0.0091^{+0.0009}_{-0.0009}$ | $0.00961 \pm 0.00014$  |
| Stellar density (gr/cm$^3$) | $0.5044^{+0.0487}_{-0.0497}$ | $0.477 \pm 0.025$     |
| Impact parameter       | $0.8410^{+0.0286}_{-0.0371}$ | $0.860 \pm 0.006$     |

$1.56 \pm 0.06 R_{\text{Jup}}$). We do not have high resolution spectrograph to do RV observation yet, but with our current instruments we may be able to rule out the grazing eclipsing binary by using transit color signature (see Tingley et al., 2014).

4. Summary
We derive some physical parameters of WASP-74b from the transit light curve data observed at Bosscha Observatory. We follow the model used in ETD, but change the fitting procedure to Bayesian approach (MCMC sampling). With low computation cost, this method can be used to fit a single-noisy light curve data like presented in this paper or amateur data collected by ETD. In the future analysis, we can add our own spectral observation and isochrone fitting to derive mass of the host star independently.

Acknowledgments
The author acknowledges funding from Faculty of Mathematics and Natural Science ITB and Leids Kerkhoven-Bosscha Fonds.

References
[1] David M Kipping 2013 MNRAS 435 2152
[2] Foreman-Mackey D, Hogg D W, Lang D and Goodman J 2013 PASP 123 306
[3] Foreman-Mackey D 2016 The Journal of Open Source Software 24 1
[4] Goodman J, & Weare J 2010 Communications in Applied Mathematics and Computational Science 5 65
[5] Hellier C et al. 2015 ApJ 150 18
[6] Hidayat T, Mahasena P, Dermawan B, Hadi T W, Premadi P W and Herdiwijaya D 2012 MNRAS 427 1903
[7] Hunter J D 2007 Comput. Sci. Eng. 9 90
[8] Mandel K & Agol E 2002 ApJ 580 L171
[9] Parviainen H 2015 MNRAS 450 3233
[10] Storn R, & Price K 1997 Journal of Global Optimization 11 341
[11] Tingley B, Parviainen H, Gandolfi D, Deeg H J, Palle E, Montañés Rodríguez P, Murgas F, Alonso R, Bruntt H, and Fridlund M 2014 A&A 567 A14