CHAPTER 4

Data analysis

4.1 Physical parameters

The orbital elements from previous studies and the parameters analyzed from TAP (Transit Analysis Package) are listed in Table 4.1 . The period (P), inclination (i) and planetary semi-major axis to star radius ratio (a/R_*) are compatible with previous results. This study was conducted using Counsins-R filter. Our star-planet radius ratio (R_p/R_*) is higher than previous R filter result from Fukui et al. (2013) and r' filter from Biddle et al. (2014). The R-band limb darkening coefficients (LD) from the fitting is also higher than the other. However, when we compare our result to PHOENIX (Allard et al., 2013) and Kurucz (Kurucz, 1979) calculations, our GJ3470 limb darkening coefficients are still in the same range.

In order to obtain planetary physical parameters, the parameters of its host star should be considered. The mean stellar density is calculated by Kepler's third law with neglect planetary mass.

$$P^2 = \frac{4\pi^2(a/R_*)^3}{G(M_*/R_*^3)} \ . \tag{4.1}$$

where G is the gravitational constant and P is the orbital period. From the MCMC result, the mean density of GJ3470 is $\rho_* = 3.02 \pm 0.71\rho_\oplus$. This result is consistent with the value derived by other works (Table 4.2). However, in this work, only R-band filter is performed. Then, the color-metallicity-radius relation cannot be used to derive stellar radius directly. From the previous studies, the stellar radius of Demory et al. (2013), $R_* = 0.568 \pm 0.037\mathrm{R}_\odot$ and Fukui et al. (2013), $R_* = 0.563 \pm 0.024\mathrm{R}_\odot$, provide the same range as this work mean stellar density. Therefore, we adopt GJ3470 radius from Fukui et al. (2013) which perform the analysis under metallicity dependence relationship (Boyajian et al., 2012) to find planet physical properties.

Table 4.1: GJ3470b orbital elements from previous studies and this work.

Reference	Orbital period (Days)	Inclination (Degree)	a/R_*	R_p/R_*	Linear LD Linear limb darkening coefficient	Quad LD Quadratic limb darkening coefficient	Filter
B12[1]	3.33714 ± 0.00017	> 88.8	14.9 ± 1.2	0.0755 ± 0.0031	0.04^2	0.19^2	$z^{'}$
					0.38^2	0.40^2	
D13[3]	3.33665 ± 0.00005	$88.3^{+0.5}_{-0.4}$	$13.42^{+0.55}_{-0.53}$	$0.07798^{+0.00046}_{-0.00045}$	0.033 ± 0.015	0.181 ± 0.10	IRAC4.5μm
F13[4]	3.336648 ± 0.000005	-	$14.02^{+0.33}_{-0.39}$	$0.07577^{+0.00072}_{-0.00075}$	$0.137^{+0.077}_{-0.073}$	0.255^2	J
				0.0802 ± 0.0013	0.19 ± 0.11	0.338^2	I_c
				0.0776 ± 0.0038	0.25 ± 0.15	0.322^2	R_c
				0.0809 ± 0.0031	0.486^2	0.289^2	$g^{'}$
N13[5]	3.336649 ± 0.000002	$88.12^{+0.34}_{-0.30}$	-	$0.07484^{+0.00052}_{-0.00048}$	0.25 ± 0.04	0.49 ± 0.03	F972N20
				0.0821 ± 0.0013	0.30 ± 0.03	0.29 ± 0.03	U
C13[6]	3.336665 ± 0.000002	$88.98^{+0.94}_{-1.25}$	-	$0.0789^{+0.0021}_{-0.0019}$	$-0.351^{+0.025}_{-0.023}$	$-0.889^{+0.051}_{-0.052}$	2.09-2.36 μm
B14[7]	$3.336648^{+0.0000043}_{-0.0000033}$	$88.88^{+0.44}_{-0.45}$	$13.94.02^{+0.44}_{-0.49}$	$0.0766^{+0.0019}_{-0.0020}$	$0.017^{+0.014}_{-0.012}$	0.5030 ± 0.0068	Gunn$Z$
				$0.0766^{+0.0019}_{-0.0020}$	$0.029^{+0.025}_{-0.018}$	0.5030 ± 0.014	Panstarrs-Z
				$0.0765^{+0.0027}_{-0.0030}$	$0.123^{+0.038}_{-0.047}$	0.488 ± 0.020	$i^{'}$
				$0.0780^{+0.0015}_{-0.0016}$	0.070 ± 0.025	$0.517^{+0.010}_{-0.0099}$	I
				$0.0736^{+0.0029}_{-0.0031}$	$0.083^{+0.035}_{-0.032}$	0.519 ± 0.016	Arizona-I
				0.0803 ± 0.0025	$0.403^{+0.40}_{-0.044}$	$0.390^{+0.036}_{-0.038}$	$r^{'}$
				$0.084^{+0.013}_{-0.016}$	-	-	Bessel-B
This work	$3.3366499^{+0.0000036}_{-0.0000035}$	$88.35^{+1.07}_{-0.81}$	$13.57^{+1.04}_{-1.10}$	$0.0843^{\pm}0.003$	$0.41^{+0.11}_{-0.12}$	$0.38^{+0.14}_{-0.12}$	Counsins-R

1 [B12] Bonfils et al. 2012,
2 Provided parameter for fitting.
3 [D13] Demory et al. 2013,
4 [F13] Fukui et al. 2013,
5 [N13] Nascimbeni et al. 2013,
6 [C13] Crossfield et al 2013,
7 [B14] Biddle et al. 2014,

From our stellar density and Fukui et al. (2013) stellar radius, the mass of GJ3470 host star is $M_{*} = 0.54 \pm 0.14 \mathrm{M}_{\odot}$. We calculate GJ3470b radius from the planet-star radius ratio and stellar radius, $R_p = 0.568 \pm 0.037 \mathrm{R}_{\oplus}$. For the planetary mass, we use the following relation, assuming a circular orbit:

$$K^{'} = KP^{1/3} = \frac{(2\pi G)^{1/3} M_p \sin i}{(M_* + M_p)^{2/3}} , \tag{4.2}$$

where K is the radial-velocity semi-amplitude. We adopt the parameter $K = 13.4 \pm 1.2$ ms^{-1}d$^{1/3}$ from Demory et al. (2013). The calculated planetary mass and density are $M_p = 13.88 \pm 2.78 \mathrm{M}_{\oplus}$ and $\rho_p = 0.55 \pm 0.14$ g.cm^{-3}, respectively.

The range of planetary equilibrium temperature, T_{eq}, can be derived from relation (Southworth (2010)),

$$T_{eq} = T_{eff} \left(\frac{1 - A}{4F} \right)^{1/4} \left(\frac{R_*}{2a} \right)^{1/2} , \tag{4.3}$$

where T_{eff} is the effective temperature of the host star, T_{eff} = 3652±50 K for GJ3470 star (Biddle et al., 2014), A is the Bond albedo[1] (0-0.4) and F is the heat re-distribution factor[2] (0.25-0.50) (Biddle et al., 2014). The temperature range in our work is T_{eq} = 512-711 K. The list of all planetary physical parameters are shown in Table 5.1.

Table 4.2: Mean stellar density of GJ3470.

Reference	stellar density ($\rho_{\odot}$)
Bonfils et al. (2012)	4.26±0.53
Demory et al. (2013)	2.91±0.37
Pineda et al. (2013)	4.25±0.40
Fukui et al. (2013)	3.32±0.27
Nascimbeni et al. (2013)	2.74±0.19
Crossfield et al. (2013)	3.49±1.13
Biddle et al. (2014)	$3.39^{+0.30}_{-0.32}$
This work	3.02±0.71

[1] a measurement of the amount of light reflected from the surface of a celestial object, such as a planet, satellite, comet or asteroid

[2] Heat redistribution factor is the dayside-nightside heat redistribution

Table 4.3: GJ3470b physical parameters.

Parameter	Value	Unit
Mass	13.88±2.78	$M_\oplus$
Radius	5.18±0.29	$R_\oplus$
Mean density	0.55±0.14	g cm^{-3}
Effective temperature	512-711	K

4.2 O-C diagram

From the previous section, GJ3470 system parameters were found. Moreover, the mid-transit times of each light curve were also found (Table 4.5). We use these mid-transit time and mid-transit time from Biddle et al. (2014), except Transit 1 which is a low quantity partial transit, to plot the epoch of each transit against the observed time minus the calculated time (O-C) in order to find the transit timing variation (TTV) of GJ3470b which may be caused by third body such as another exoplanet in the system or GJ3470b exomoon (Figure 4.1).

We perform linear fitting to O-C diagram to correct GJ3470b ephemeris. The corrected ephemeris of GJ3470b is

$$T_0(E) = 245\,5983.703\,90 + 3.336\,6499E\ , \qquad (4.4)$$

where E is the number of epoch from 26 February 2012 transit, i.e., Transit 1 of Biddle et al. (2014). The O-C diagram shows that there is no significant variation of GJ3470b mid transit time. Most of them are consistent with 2-σ[3] variation. From this result, we can conclude that there is no nearby stellar object which has strong gravitational interaction with GJ3470b.

[3] σ is defined as the acceptable limit for the error of our calculation

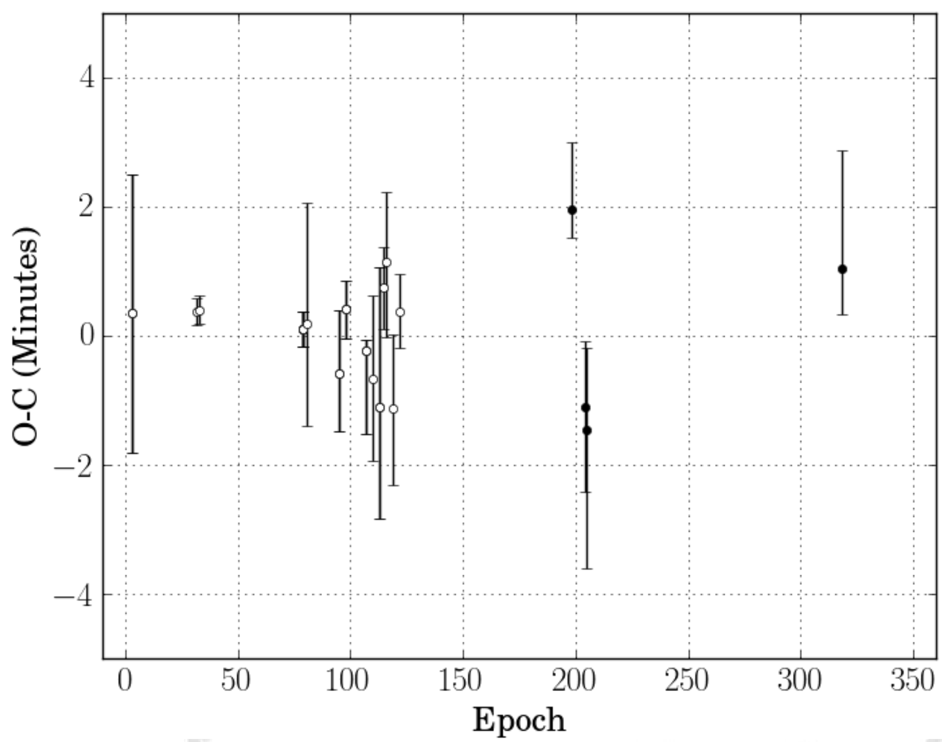

Figure 4.1: O-C diagram of exoplanet GJ3470b. *White dot*: Literature review. *Black dot*: This study.

Table 4.4: Mid transit time from previous paper.

Observers	Mid-transit time (BJD)
Bonfils (2012)	245 5983.7417 ± 0.001 5
	245 5993.7141 ± 0.001 5
Demory (2013)	245 6090.4771 ± 0.000 14
	245 6093.8137 ± 0.000 15
Fukui (2013)	245 6247.2995 ± 0.000 19
Nascimbeni (2013)	245 6340.7256 $^{+0.000\ 90}_{-0.000\ 11}$
Crossfield (2013)	245 6390.7758 ± 0.000 4
Biddle (2014)	245 6253.9729 $^{+0.001\ 1}_{-0.001\ 3}$
	245 6300.6855 $^{+0.000\ 63}_{-0.000\ 68}$
	245 6310.6961 $^{+0.000\ 32}_{-0.000\ 31}$
	245 6350.7352 $^{+0.000\ 88}_{-0.000\ 90}$
	245 6360.7449 $^{+0.001\ 2}_{-0.001\ 5}$
	245 6367.4195 $^{+0.000\ 45}_{-0.000\ 43}$
	245 6370.7564 $^{+0.000\ 81}_{-0.000\ 76}$
	245 6380.7648 $^{+0.000\ 83}_{-0.000\ 80}$

Table 4.5: Mid transit for each light curve.

Observing date	Mid-transit time (BJD)
17 December 2013	245 6644.3625$^{+0.000\ 30}_{-0.000\ 73}$
06 January 2014	245 6664.3803$^{+0.000\ 92}_{-0.000\ 71}$
10 January 2014	245 6667.7161$^{+0.001\ 48}_{-0.000\ 88}$
22 January 2015	245 7044.7602$^{+0.000\ 49}_{-0.001\ 28}$