Measurements of Transit Timing Variations for WASP-5b

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Abstract

We observed 7 new transits of the “hot Jupiter” WASP-5b using a 61 cm telescope located in New Zealand, in order to search for transit timing variations (TTVs), which can be induced by additional bodies existing in the system. Combining them with other available photometric and radial velocity (RV) data, we find that its transit timings do not match a linear ephemeris; the best-fit χ² value is 32.2 with 9 degrees of freedom, which corresponds to a confidence level of 99.982% or 3.7σ. This result indicates that excess variations of transit timings have been observed, either due to unknown systematic effects, or possibly due to real TTVs. The TTV amplitude is as large as 50 s, and if this is real it cannot be explained by some effect other than an additional body, or bodies. From RV data, we put an upper limit on the RV amplitude caused by a possible secondary body (planet) as 21 m s⁻¹, and if this is real it cannot be explained by some effect other than an additional body, or bodies. From RV timings do not match a linear ephemeris; the best-fit χ² value is 32.2 with 9 degrees of freedom, which corresponds to a confidence level of 99.982% or 3.7σ. This result indicates that excess variations of transit timings have been observed, either due to unknown systematic effects, or possibly due to real TTVs. The TTV amplitude is as large as 50 s, and if this is real it cannot be explained by some effect other than an additional body, or bodies. From RV data, we put an upper limit on the RV amplitude caused by a possible secondary body (planet) as 21 m s⁻¹, which corresponds to its mass of 22–70 M⊕ over the orbital period ratio of the two planets from 0.2 to 5.0. From the TTV data, using numerical simulations, we narrowed the limits down to 2 M⊕ near 1:2 and 2:1 mean-motion resonances (MMRs) with WASP-5b at the 3σ level, assuming that the two planets are co-planer. We also put an upper limit of 43 M⊕ (3σ) on excess of Trojan mass using both RV and photometric data. We also find that if the orbit of the possible secondary planet is a circle or an ellipse of small eccentricity, it would be likely an orbit near that of low-order MMRs.

Key words: stars: planetary systems: individual (WASP-5) — techniques: photometric

1. Introduction

More than 400 extrasolar planetary systems have been found to date by several techniques, such as pulsar timing, radial velocity (RV), transit, microlensing, and direct imaging. Among them, more than 40 systems have been revealed to have multiple planets, most of which have been detected by the RV technique (Wright et al. 2009). Considering observational limits, multiplanetary systems are thought to be common, which is naturally expected from the standard planetary formation mechanism, called core accretion models (e.g., Hayashi 1981; Pollack et al. 1996; Kokubo & Ida 2002). Increasing the number of multiplanetary systems and studying their nature are important for improving our understanding of planetary formation mechanisms and dynamics of planetary systems.

Searching for transit timing variations (TTVs) from a constant period ephemeris is another method for identifying multiplanetary systems. If a transiting planet is the one and...
only body orbiting its host star, its orbital period should be constant. On the other hand, if another perturbing body exists in the system, the orbital period will no longer be constant. Therefore, we can find additional planets by probing TTVs, in the system, the orbital period will no longer be constant. On the other hand, if another perturbing body exists only body orbiting its host star, its orbital period should be constant. According to core accretion models, hot Jupiters are predicted to form at several AU where solid material is abundant enough to become a massive core and to accrete gas, and then migrate inward and to their current positions in some way; mainly either via gravitational disk–planet interaction models (hereafter disk–planet interaction models, e.g., Lin & Papaloizou 1986), or via planet–planet scattering and/or Kozai process followed by tidal evolution (hereafter planet–planet scattering models, e.g., Nagasawa et al. 2008). The disk–planet interaction models predict that two planets including a gas-giant planet in a system will be easily captured in low-order MMRs during their migration processes (e.g., Thommes 2005). On the other hand, the planet–planet scattering models are thought to be difficult to form planets captured in MMRs. The current distribution of the sky-projected angle between the stellar spin and the planetary orbital axis measured via the Rossiter–McLaughlin effect shows that a significant amount of hot Jupiters are misaligned (e.g., Narita et al. 2009; Winn et al. 2009b; Triaud et al. 2010, hereafter T10). This fact implies that the planet–planet scattering models might play an important role in forming hot Jupiters. Furthermore, Winn et al. (2010) pointed out that hot Jupiters around hot stars tend to have high obliquities rather than those around cool stars, and they proposed a hypothesis that most or all hot Jupiters initially have high obliquities and only cool stars have damped their obliquities. If this explanation is true, planets in MMRs with hot Jupiters would be rare. The TTV method can thus be a powerful tool for checking the existence or nonexistence of such planets around hot Jupiters and testing these planetary migration scenarios.

Although the TTV method has been employed in many searches for additional planets, to date most of them have not shown any planetary signals, while they have been used to put upper limits on the masses of hypothetical additional planets in the system (e.g., Adams et al. 2010, and a summary therein). Recently, three systems have been reported to show plausible TTV signals: WASP-3 (Maciejewski et al. 2010), WASP-10 (Maciejewski et al. 2011), and Kepler-9 (Holman et al. 2010).

The transiting planet WASP-5b was discovered by Anderson et al. (2008, hereafter A08) as a 1.58 $M_{Jup}$ hot Jupiter orbiting a $V = 12.3$ (G4V) star with a period of 1.63 d. Gillon et al. (2009, hereafter G09) conducted photometric and spectroscopic follow-up observations of high precision for this system using the 8.2 m Very Large Telescope (VLT). Although their photometric data were not analyzed accurately due to uncorrectable systematic errors, and were not used for their analysis, they checked and reanalyzed the photometric and RV data presented in A08, and found the planetary orbit to be marginal nonzero eccentricity ($\sim 2\sigma$). They also found that the reduced $\chi^2$ of a linear fit for four transit timing data was 5.7, which might be a sign of additional bodies. Southworth et al. (2009, hereafter S09) presented two high-quality photometric transit light curves obtained with the 1.54 m Danish telescope and with residual standard deviations relative to theoretical fits of 0.50 and 0.59 mmag. They argued that the inconsistency between the transit data and a linear ephemeris could be associated with a relatively poor transit light curve from the Faulkes Telescope South (FTS). T10 presented 33 new RV data obtained with the HARPS spectrograph, including data during a transit, and 5 CORALIE data in addition to the eleven given by A08. They derived a sky-projected spin–orbit angle of $\lambda = 12^\circ.1^{+8.0\circ}_{-10.0\circ}$, which is consistent with a spin–orbit alignment that is naturally expected from the disk–planet interaction models for the migration mechanism of WASP-5b. However, the planet–planet scattering models followed by the stellar obliquity dumping could still be an alternative scenario, because the host star is a “cool star” in the context of Winn et al. (2010), which might therefore easily dump the stellar obliquity. We cannot exclude this scenario at this point in time, and therefore searching for additional planets in low-order MMRs via the TTV method is useful for testing these migration scenarios.

In this paper, we present observations of 7 new transits of WASP-5b obtained with a 61 cm telescope. We also gathered available photometric and RV data and performed joint-fits to refine any transit parameters and to search for TTV signals. In section 2 we describe our observations and data reduction. We show our light-curve modeling in section 3 and discuss results in section 4. We summarize our findings in section 5.

2. Observations and Data Reduction

2.1. Transit Observations

We observed 7 transits of WASP-5b (corresponding transit epochs, $E$, are: 160, 244, 432, 451, 459, 607, and 615 based on the ephemeris given by A08) using the 61 cm Boller and Chivens (B&C) telescope located at Mt. John University...
Observatory, operated by the University of Canterbury at Lake Tekapo in New Zealand. The B&C telescope is normally used for the microlensing follow-up program of Microlensing Observations in Astrophysics collaboration (MOA: Bond et al. 2001; Sumi et al. 2003, 2010), and transit observations were obtained during the low-priority observing time. A 1 k CCD camera of Apogee ALTA U47 is mounted on the telescope, which has a focal length of 8.3 m. The CCD pixel size is 13 μm × 13 μm and its scale 0′′.33 per pixel. Therefore, the camera covers a field of view of 5′′5 × 5′′5. The CCD frame readout time is 5 s and has a readout noise, n_pix, of 11.5 electrons per pixel. The dark current noise, n_dark, is 0.03 ADU per pixel per second under normal conditions. A Bessell J filter was used for all observations, and the exposure times were 30 s for E = 244 and 607 and 60 s for the others. All images were taken with the telescope properly focused, except for the transit of E = 459 when the telescope was slightly defocused so that the FWHM of the PSF was 9–12 pixels (3.′0–4.′0). The typical seeing at the observatory was ≈2.′0. An observing log is shown in table 1.

2.2. Data Reduction

All images were initially bias subtracted and flat-field corrected in the standard manner. We then performed synthetic aperture photometry for the target star WASP-5 and some (2–4) comparison stars in the same field of view, using the following procedure. Note that each star to be measured is enough isolated from the closest star so as not to be contaminated during the procedure.

First, for each image j, using a step size of 0.1 pixels, we searched for an initial photometric aperture radius, r_opt,j, that maximized the signal-to-noise ratio of the target flux. The signal, F star, is the flux from the target, which is equal to the total flux in the aperture minus the corresponding sky flux, F sky = m_pix f_sky. Here, m_pix is the total number of pixels in the aperture and f_sky is the median flux per pixel in an annulus of which the inside and outside radii are radii r_opt,j + 50 and r_opt,j + 60, where the flux contribution from the target star is negligible. The total noise contributing to the signal is modeled as

\[ N_{\text{signal}} = \sqrt{N_{\text{star}}^2 + N_{\text{sky}}^2 + N_{\text{read}}^2 + N_{\text{dark}}^2 + N_{\text{scint}}^2}, \]

where

\[ N_{\text{star}} = \sqrt{\frac{F_{\text{star}}}{g}} \]

is the photon noise of the target star, N_{sky} = \sqrt{\frac{F_{\text{sky}}}{g}} the sky background noise, N_{read} = \sqrt{m_{\text{pix}} n_{\text{read}}/g} the readout noise, N_{dark} = \sqrt{m_{\text{pix}} n_{\text{dark}} \Delta t} the dark-current noise, and N_{scint} the atmospheric scintillation. Here, g = 1.19 electron per ADU is the CCD gain and \( \Delta t \) is the exposure time in seconds; n_{read} and n_{dark} are defined in the previous subsection.

The scintillation noise can be expressed as

\[ N_{\text{scint}} = \sigma_0 \frac{z^2}{D^{2/3}} \exp \left( -\frac{h}{8000m} \right) F_{\text{star}}, \]

where z is the airmass, D the telescope diameter in cm, and h = 1029 m the observatory altitude (Young 1967; Dravins et al. 1998). Furthermore, \( \sigma_0 \) is a coefficient that is often taken to be 0.064, and we also adopted this value. Under normal conditions with an exposure time of 60 s, the main contributor to the total noise was the photon noise (≈0.0012% of the target flux); the contributions from the other noises were one or two orders of magnitudes less than that.

Next, after determining the r_{opt,j} value for the target star, this radius was applied to all other comparison stars on the same image to measure their fluxes. The target flux was then normalized to a reference flux that was created as the weighted average of the fluxes of the comparison stars. The photometric error of the normalized flux was initially estimated using equation (2) and the error propagation equation.

Finally, for each transit E, we searched for a scaling factor, \( y_E \) (in the range of 0.7 to 1.50), to the initial radius r_{opt,j} in order to minimize the rms scatter of the derived out-of-transit (OOT) light curve (either before or after transit).

In order to assess the validity of our method, we also performed aperture photometry with a fixed radius r_{fix,E} for each transit, which was selected so as to produce the minimum rms scatter for the OOT light curve. The result of this exercise was that the OOT rms values derived from the \( y_E r_{\text{opt,j}} \) apertures were slightly better than those from the r_{fix,E} apertures for all transit light curves, except for the transit E = 615, for which there are a relatively small number of OOT data points, possibly leading to a large statistical fluctuation. Table 2 shows a comparison of OOT rms values derived by the two methods. In order to maintain consistency, all light curves were generated by using the scaled aperture method, and these were used for further analyses.

All time stamps of observations, which were recorded in the FITS headers as the observation start and end points in units of Julian Day (JD) based on Coordinated Universal Time (UTC) and obtained from the network time protocol, were converted to the mid-observation points in units of Barycentric Julian Day (BJD) based on Barycentric Dynamical Time (TDB) using the code UTC2BJD (Eastman et al. 2010). The time given the network time protocol has occasionally been confirmed to coincide with the GPS time within 1 s by observers. The time-conversion error does not exceed 20 ms.

| Date          | Epoch | Exp. [s] | Filter | # of data | Focus/defocus | Airmass |
|---------------|-------|----------|--------|-----------|--------------|---------|
| 2008 June 18  | 160   | 60       | I      | 248       | focus        | 1.55 → 1.00 |
| 2008 November 2 | 244   | 30       | I      | 393       | focus        | 1.00 → 1.35 |
| 2009 September 4 | 432   | 60       | I      | 168       | focus        | 1.03 → 1.00 → 1.07 |
| 2009 October 5 | 451   | 60       | I      | 313       | focus        | 1.07 → 1.00 → 1.39 |
| 2009 October 18 | 459   | 60       | I      | 248       | defocus      | 1.01 → 1.80 |
| 2010 June 16  | 607   | 30       | I      | 307       | focus        | 2.60 → 1.23 |
| 2010 June 29  | 615   | 60       | I      | 202       | focus        | 1.78 → 1.04 |
3. Light Curve Modeling

3.1. Systematic Correction

Since apparent systematic trends were seen in the derived light curves, we corrected these systematic effects. The systematic trends could arise from the changing airmass, variations in the atmospheric extinction coefficient, slow variability in the brightness of the target or comparison star, and so forth. By using the correction factor, $\Delta m_{\text{corr}}$, in the magnitude scale, the corrected flux, $F_{\text{corr}}$, can be expressed as

$$F_{\text{corr}} = F_{\text{obs}} \times 10^{-0.4 \Delta m_{\text{corr}}},$$

(3)

where $F_{\text{obs}}$ is the observed flux of the target normalized by the reference flux. If we assume that amplitudes of the intrinsic stellar variability and variations in the second-order atmospheric extinction coefficient both are proportional to time, $\Delta m_{\text{corr}}$ can be expressed as

$$\Delta m_{\text{corr}} = k_0 + k_2 z + k_3 t + k_{12} t z,$$

(4)

where $z$ is the airmass, $t$ the time, and $(k_0, k_2, k_3, k_{12})$ the relevant coefficients. This equation is similar to equation (1) of Winn et al. (2009a), although we here use four coefficients instead of three (see the Appendix). Provided that there were enough data points, only the OOT light curve segments were fitted to estimate the systematic-correcting function. However, three of the light curves ($E = 244, 432, \text{and } 607$) did not have an adequate amount of data points in their OOT sections, and also apparent systematic variations were seen in the first half part of the light curve of $E = 451$ transit which could not be corrected if only the OOT data were used. Therefore, we decided to fit each light curve including the transit section while fixing the parameters defining the transit shape to the values derived by S09, who obtained two transit light curves with higher precision than ours.

To create a parameterized transit light curve, an analytic model of Mandel and Agol (2002) was used. This model requires 6 parameters: the planet/star radius ratio, $R_p/R_*$, the semimajor axis of the planetary orbit in units of the star radius, $a/R_*$, the orbital inclination to the line of sight, $i$, the orbital period, $P$, and two stellar limb-darkening coefficients, $u_1$ and $u_2$. We used a quadratic limb darkening law,

$$I(\mu) = 1 - u_1 (1 - \mu) - u_2 (1 - \mu)^2,$$

(5)


Table 2. Comparisons of rms scatters.

| Epoch | $N_{\text{OOT}}$† | $\gamma_E$ | $\gamma_{E\text{fix}}$ | $r_{\text{fix,E}}$ | Rms scatter for OOT (%) |
|-------|-------------------|-----------|------------------------|-------------------|------------------------|
| 160   | 75 (a)            | 0.96      | 9.6–13.1               | 13.1              | 0.177                  |
| 244   | 119 (a)           | 1.27      | 13.1–18.5              | 15.8              | 0.488                  |
| 432   | 50 (b)            | 1.34      | 11.5–14.5              | 14.1              | 0.205                  |
| 451   | 77 (a)            | 1.47      | 14.4–16.0              | 14.0              | 0.282                  |
| 459   | 52 (b)            | 1.24      | 13.9–17.1              | 13.9              | 0.179                  |
| 607   | 49 (a)            | 1.42      | 12.5–14.3              | 13.0              | 0.287                  |
| 615   | 44 (a)            | 1.30      | 11.1–13.7              | 12.7              | 0.161                  |

* Comparisons of rms scatters between out-of-transit (OOT) light curves derived by using optimized radii ($\gamma_{E\text{fix,J}}$) and that derived by using fixed radii ($r_{\text{fix,E}}$).
† $N_{\text{OOT}}$ is the number of OOT (either before or after the transit) data points and “b” and “a” in parentheses stand for “before” and “after” the transit, respectively.

Table 3. Light curve of WASP-5b – Epoch160.*†

| BJD$_{\text{TDB}}$ | Light curve | Uncertainty |
|-------------------|-------------|-------------|
| 2454636.091621     | 0.9966666   | 0.002606    |
| 2454636.092385     | 0.997704    | 0.002600    |
| 2454636.093149     | 1.001889    | 0.002594    |
| 2454636.093913     | 0.995729    | 0.002581    |
| 2454636.094677     | 1.001046    | 0.002586    |

* Note that uncertainties have already been rescaled by factor $\beta$ according to the context of the paper.
† This is a sample of the corrected light curves and the entire data for 7 epochs (160, 244, 432, 459, 607, and 615) are available in the electronic version (http://pasj.asj.or.jp/v63/n1/630123/).
Fig. 1. Systematic-corrected light curves of WASP-5b (black points) and their residuals (gray points) from the best-fit model (solid lines), which was determined by simultaneous fits for seven transit light curves with their normalized error bars taking red noises into account; 0.968 is added to each residual light curve for display. $E$ numbers stand for the corresponding transit epochs.

Table 4. Derived values.*

| Epoch | $\beta$ | $N_{\text{max}}$ | $\sigma_1$ [%] | Numbers of data | Telescope |
|-------|---------|-----------------|----------------|-----------------|-----------|
| 160   | 1.15    | 15              | 0.197          | 248             | B&C       |
| 244   | 1.16    | 14              | 0.364          | 386             | B&C       |
| 432   | 1.09    | 6               | 0.205          | 168             | B&C       |
| 451   | 1.76    | 18              | 0.234          | 313             | B&C       |
| 459   | 1.01    | 8               | 0.220          | 247             | B&C       |
| 607   | 1.31    | 17              | 0.322          | 306             | B&C       |
| 615   | 1.19    | 13              | 0.210          | 202             | B&C       |
| 5     | 1.16    | 10              | 0.094          | 138             | Euler     |
| 7     | 2.28    | 27              | 0.262          | 335             | FTS       |
| 204   | 1.28    | 15              | 0.046          | 73              | Danish    |
| 218   | 1.34    | 15              | 0.054          | 101             | Danish    |

* Estimated red-noise factor ($\beta$), the number of data points in one bin ($N_{\text{max}}$), unbinned rms scatter from the best-fit model ($\sigma_1$), and the total number of data points for each transit light curve are listed.
deviation after binning the residuals into $M$ bins of $N$ points, $\sigma_N$, would be expected to be

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

where $\sigma_1$ is the standard deviation of the unbinned residuals. The actual measured value of $\sigma_N$ is usually larger by a factor $\beta$. Since the value of $\beta$ depends on the choice of $N$ and $M$, we adopted the maximum $\beta$ value in the range of $N = 5$ to 30 and rescaled each error bar by this value. The derived values of $\beta$ and the entire rms scatters of residuals are given in table 4.

3.2. Joint Fit

To assess the quality of our light curves against that of the previous work, we fitted the seven transit light curves from the B&C telescope simultaneously and compared the resultant parameters with those of S09 and T10, in which independent data sets were used. At this time we used the same parameterization as in the previous subsection, and used formula of Ohta, Taruya, and Suto (2009) for creating a transit light-curve model. We used common parameters of $i$, $R_p/R_*$, $a/R_*$, $u_1$, and $u_2$ to all transit light curves, while we used respective midtransit times, $T_{c,E}$. This fitting allowed the parameters of $i$, $R_p/R_*$, $a/R_*$, $u_1$, and each $T_{c,E}$ to vary, while $u_2$ was fixed at the theoretical value of 0.321. We fixed $u_2$ in the fitting process, since the $u_1$ and $u_2$ quantities are so strongly correlated that they both could not be well determined from the light-curve fitting. The eccentricity was also fixed to zero.

We then derived the best fit parameters by minimizing the $\chi^2$ statistics using the AMOEBA algorithm (Press et al. 1992) and estimated uncertainties using the $\Delta \chi^2 = 1.0$ criterion, following Narita et al. (2007). The resultant parameters and their $1\sigma$ uncertainties are given in table 6. The parameters derived from the B&C are consistent with those of S09 and T10 within their error bars, except for the period $P$, which may be a sign of the TTVs (discussed in section 4).

Figure 3 compares phase folded, 120 s binned light curves from the B&C and the Danish (online data of S09) telescopes. Before folding the Danish data, the quoted errors were normalized and rescaled by using the same method as the B&C data described in the previous section, i.e., normalized so that the reduced $\chi^2$ for the best-fit to each transit was unity and rescaled by a factor $\beta$ accounting for the red noise; we then took a weighted average and calculated its error for each binned data set.

The rms residuals from the best-fit models for the Danish

### Table 5. Limb-darkening coefficients.*

| Telescope | Filter | $u_1$ (fitted) | $u_2$ (fixed) |
|-----------|--------|----------------|---------------|
| Euler     | $R$    | 0.33 $\pm$ 0.05 | 0.32          |
| FTS       | SDSS $i'$ | 0.49 $\pm$ 0.12 | 0.32          |
| B&C       | $I$    | 0.27 $\pm$ 0.05 | 0.32          |
| Danish    | $R$    | 0.34 $\pm$ 0.04 | 0.32          |

* Quadratic limb-darkening coefficients ($u_1$ and $u_2$) for each telescope used for the final joint fit. Each $u_1$ was allowed to be free while each $u_2$ was fixed at the theoretical value extracted from tables of Claret (2000) or Claret (2004).

### Table 6. Best-fit parameters and their 1σ uncertainties.*

|                         | This work (B&C only) | This work (all) | Southworth et al. (2009) | Trau et al. (2010) |
|-------------------------|----------------------|----------------|--------------------------|-------------------|
| $P$ [d]                 | 1.6284301 $\pm$ 0.0000012 | 1.6284314 $\pm$ 0.0000056 | 1.6284246 $\pm$ 0.0000013 | 1.6284229 $\pm$ 0.0000044 |
| $T_0$ [BJD$_{TDB}$ - 2450000] | 4375.62589 $\pm$ 0.00052 | 4375.62510 $\pm$ 0.00019 | 4375.62569 $\pm$ 0.00024 | 4373.99674 $\pm$ 0.00015 |
| $i$ [°]                 | 85.01 $^{+0.17}_{-0.78}$ | 85.58 $^{+0.1}_{-0.76}$ | 85.8 $\pm$ 1.1 | 86.2 $^{+0.1}_{\pm}$ |
| $R_p/R_*$               | 0.1110 $^{+0.010}_{-0.014}$ | 0.1108 $\pm$ 0.011 | 0.1110 $\pm$ 0.0014 | 0.1105 $\pm$ 0.0007 |
| $a/R_*$                 | 5.26 $^{+0.23}_{-0.17}$ | 5.37 $\pm$ 0.15 | 5.41 $^{+0.17}_{-0.18}$ | 5.49 $^{+0.17}_{-0.12}$ |
| $K$ [m s$^{-1}$]        | 269.4 $\pm$ 3.3 | — | 268.7 $^{+1.7}_{-1.9}$ | — |
| $e$                     | 0 (adopted) | 0 (adopted) | 0 (adopted) | $<0.0371$ |
| $V\sin I$ [km s$^{-1}$] | 3.05 $\pm$ 0.41 | — | 3.24 $^{+0.35}_{-0.34}$ | 8.8 $^{+4.1}_{-1.9}$ |
| $\lambda$ [°]          | 7.2 $\pm$ 9.5 | — | 12.4 $^{+1.9}_{-1.7}$ | — |

* Best-fit parameters and their 1σ uncertainties for WASP-5b derived from joint fits for only the 7 light curves from the B&C telescope (the second column) and for all available RV and photometric data (the third column) are listed. Parameters derived by S09 (the fourth column) and T10 (the rightmost column) are shown for comparison.
data and B&C data are 0.00046 and 0.00081, respectively. However, the uncertainties in the transit-model parameters from the B&C data are comparable to those from the Danish data presented in S09 (see table 6). This result initially appears surprising given the difference in the fit residuals; however, we found that the values of the error-rescaling factor $\beta$ for the Danish data are larger than most of those for the B&C data (see table 4). As a consequence, the average values of the binned errors of the Danish and B&C data sets (0.00061 and 0.00084 respectively) are more comparable. Moreover, the $R$-band filter used for the Danish observations would have resulted in a larger limb-darkening effect than that seen by using the $I$-band filter employed in the B&C observations. This leads to a relatively poorer determination of the model parameters for the Danish data (e.g., Pál 2008). In addition, S09 included limb-darkening model dependencies in their error estimation which enlarged the errors of the transit-model parameters. However, all general limb-darkening models produce a symmetrical transit shape, which has little effect on the error of transit timings. For this reason, we do not include model dependencies derived from limb-darkening in this paper.

To refine the transit model parameters and to revise the timings of the previous transits, we assembled all available photometric and RV data in addition to our own data, and fitted them jointly. The photometric data set consists of 11 transits including one transit from the 1.2 m Euler telescope (133 data points) and one from the 2.0 m FTS telescope (335 data points) analyzed in A08 (private communication), two from the 1.54 m Danish telescope (174 data points) presented in S09, and seven from the B&C telescope (1870 data points). The RV data set consists of 16 and 33 data points from CORALIE and HARPS instruments, presented in T10. In these available data sets, all time stamps are provided either in the form of heliocentric JD (HJD) (Euler, FTS, and Danish) or BJD (CORALIE and HARPS). However, time standards (e.g., UTC or TDB) on which these time systems are based are unspecified in the publications. As Eastman et al. (2010) alerted recently, specifying the time standard is important in order to achieve 1 min accuracy, and TDB-based BJD is the recommended time system. We confirmed (in private communications) that all time systems in the available data were based on UTC, and we therefore converted all of them to the TDB-based BJD.

In order to treat the acquired photometric data equally with the B&C data, their quoted errors were normalized and rescaled in the same manner as for the B&C, as explained in the previous subsection. The derived value of $\beta$ and the rms scatter of the residuals for each transit are given in table 4. For the RV data, systematic errors of $\sim 7$ m s$^{-1}$ may be presented (A08 and T10) in addition to the quoted internal errors; these often come from stellar activity (stellar jitter). To add statistical weight to the RV data, we rescaled the quoted RV errors for both CORALIE and HARPS by adding 7 m s$^{-1}$ quadratically. This value is consistent with the upper one from an empirical model of Wright (2005) for a G-type star.

We then fitted these data with three additional parameters: the RV semi-amplitude, $K$, the sky-projected stellar rotational velocity, $V\sin I_s$, and the sky-projected spin–orbit alignment angle, $\lambda$. The last two parameters were needed to model the Rossiter–McLaughlin (RM) effect during transits of WASP-5b. The RM formula we used was based on Hirano et al. (2010), which is more appropriate than the old one used in previous work (T10). The formula allowed the parameters of $i$, $R_p/R_s$, $a/R_s$, $T_{c,E}$, $K$, $V\sin I_s$, and $\lambda$ to be free. We also fitted $u_1$ for each telescope, while each $u_2$ was fixed at the theoretical value (Claret 2000, 2004), because, as mentioned previously, it was difficult to simultaneously determine unique values for both $u_1$ and $u_2$ due to their strong correlation. About the eccentricity, we first allowed it to be free, and obtained a value of $0.002_{-0.002}^{+0.010}$. This value is consistent with zero within 1 $\sigma$, but also consistent with the result of T10 ($e < 0.0371$, 2 $\sigma$), but marginally inconsistent with G09 ($e = 0.049_ {+0.020} ^{-0.017}$). However, the latter used a smaller RV data set in comparison with us, and hence we adopted zero for the eccentricity and refitted the data. The derived value of $u_1$ and the fixed value of $u_2$ for each telescope are listed in table 5, and the other best-fit parameters are given in table 6.

From the combined fit, we refined some transit model parameters, $i$, $R_p/R_s$, and $a/R_s$ against the published values, while they are consistent within their error bars. Uncertainties in $K$ and $V\sin I_s$ became larger than those determined by T10 because we incorporated the stellar jitter in the RV errors. We chose the value of the stellar mass as that determined spectroscopically by T10 because it corresponded to the stellar jitter in the RV errors. We chose the value of the stellar mass as that determined spectroscopically by T10 because we incorporated the stellar jitter in the RV errors. We chose the value of the stellar mass as that determined spectroscopically by T10 because we incorporated the stellar jitter in the RV errors. We chose the value of the stellar mass as that determined spectroscopically by T10 because we incorporated the stellar jitter in the RV errors. 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4. Results and Discussion

4.1. Significance of TTV Signal

We give the transit timings with 1 σ uncertainties in table 7. By using these data, a new ephemeris was calculated via a linear fit using a function,

$$T_{c,E} = T_{c,0} + EP,$$  \hspace{1cm} (7)

where $T_{c,0}$ is a reference time of $E = 0$. The results are $T_{c,0}$ [BJD$_{TDB}$] = 2454375.62510 ± 0.00019 and $P$ = 1.62843142 ± 0.000000644. This fit yields $\chi^2 = 32.2$ for 9 degrees of freedom, which indicates that a linear fit does not rise to a confidence level of 99.982%, or 3.7σ. Figure 4 shows the timing residuals and their uncertainties. This result implies that we see excess variations in transit time either due to unknown systematic effects or possibly due to real TTVs. A linear fit for the B&C data only yields $\chi^2 = 17.1$ for 5 degrees of freedom, which corresponds to a confidence level of 99.57% or 2.7σ, while the fit for the other 4 data yields $\chi^2 = 9.8$, which corresponds to a confidence level of 99.27% or 2.9σ. Even if two data having the largest uncertainties (corresponding to epochs of $E = 7$ and 451) in all 11 timing data, which may have larger systematic errors, are discarded, the $\chi^2$ value for a linear fit remains 27.1 for 7 degrees of freedom, which corresponds to a confidence level of 99.968% or 3.6σ. This result increases the statistical significance of a TTV excess implied by G09, who used four timing data (two of them were derived from the same photometric data as we use) and found $\chi^2/\text{dof}$ value for a linear fit to be 5.7, which corresponds to a significance of 99.67% or 2.9σ.

The standard deviation of the observed timing residuals is 68 s, and the mean uncertainty of the timings is 41 s; therefore, if this is a real TTV signal, the actual standard deviation of the TTV is expected to be 50 s. Such a large timing deviation could not be explained by any effect other than additional perturbing bodies. The sizes of these alternative possibilities are: the Applegate effect ($\sim 1.5$ s per 11 yr: Watson & Marsh 2010), the light travel time effect due to an outer massive body ($\lesssim 1$ s per 3 yr: e.g., Agol et al. 2005), the orbital decay caused by tidal dissipation ($\sim 5$ ms yr$^{-1}$: Hellier et al. 2009), and the orbital precessions due to tidal deformations ($< 130$ ms yr$^{-1}$), due to the general-relativity effect ($< 2$ ms yr$^{-1}$), and due to the stellar quadrupole moment ($< 0.005$ ms yr$^{-1}$: Heyl & Gladman 2007; Jordán & Bakos 2008) (see table 9). In addition, the presence of an exomoon also could not be responsible for the signal, because Weidner and Horne (2010) placed an upper mass, $9.1 \times 10^{-4} M_{\oplus}$, and a distance, 4.39 $R_{\text{Jup}}$, of a possible moon for the WASP-5b system by considering the three-body stability issue; such a moon would result in only $\sim 0.02$ s TTVs. Thus, the remaining possibilities for explaining the signal are additional planets or Trojan companions (bodies at 1:1 MMR).

### Table 7. Transit timings and their uncertainties.

| Epoch | Transit timing [BJD$_{TDB}$ = 2450000] | 1 σ uncertainty | Telescope |
|-------|----------------------------------------|-----------------|------------|
| 5     | 4383.76751 0.00028 Euder               |                 |            |
| 7     | 4387.02286 0.00086 FTS                 |                 |            |
| 160   | 4636.17465 0.00047 B&C                 |                 |            |
| 204   | 4707.82531 0.00021 Danish              |                 |            |
| 218   | 4730.62252 0.00022 Danish              |                 |            |
| 244   | 4772.96212 0.00051 B&C                 |                 |            |
| 432   | 5079.10849 0.00044 B&C                 |                 |            |
| 451   | 5110.04645 0.00073 B&C                 |                 |            |
| 459   | 5123.07627 0.00041 B&C                 |                 |            |
| 607   | 5364.08262 0.00057 B&C                 |                 |            |
| 615   | 5377.10969 0.00048 B&C                 |                 |            |

### Figure 4. Transit timing residuals of WASP-5b using a new ephemeris determined in section 4. A filled square is the Euler data, an open square the FTS data, two triangles the Danish data, and seven filled circles the B&C data.

### Table 8. Derived physical values and their uncertainties for the WASP-5b system.

| Parameter | This work | Southworth et al. (2009) | Triaud et al. (2010) |
|-----------|-----------|-------------------------|---------------------|
| $a$ [AU]  | 0.02702 ± 0.00059 | 0.02729 ± 0.00049 ± 0.00027 | 0.02709 ± 0.00056 < 0.00062 |
| $R_{\star}$ [R$_{\odot}$] | 1.082 ± 0.038 | 1.084 ± 0.040 ± 0.011 | 1.056 ± 0.080 ± 0.029 |
| $M_{\star}$ [M$_{\odot}$] | 1.000 ± 0.065 | 1.021 ± 0.055 ± 0.030 | 1.000 ± 0.063 ± 0.067 |
| $\rho_{\star}$ [M$_{\odot}$] | 0.79 ± 0.10 | 0.803 ± 0.080 ± 0.000 | 0.84 ± 0.07 ± 0.15 |
| $R_{p}$ [R$_{\text{Jup}}$] | 1.167 ± 0.043 | 1.171 ± 0.056 ± 0.012 | 1.14 ± 0.10 ± 0.04 |
| $M_{p}$ [M$_{\text{Jup}}$] | 1.568 ± 0.071 | 1.637 ± 0.075 ± 0.033 | 1.555 ± 0.067 ± 0.070 |
| $\rho_{p}$ [M$_{\text{Jup}}$] | 0.92 ± 0.11 | 1.02 ± 0.14 ± 0.01 | 1.05 ± 0.20 |

* The value of the stellar mass was adopted to the value derived by T10. The values presented in S09 and T10 are shown for comparison.
4.2. Upper Mass Limits for Secondary Planet

Marginal evidence for the TTV signal is seen; however, it is hard to determine the characteristics of the additional body (planet) at this time because of a large parameter space for the planet parameters: mass, orbital period, eccentricity, position of periapsis, reference phase, and mutual inclination. Alternatively, using the observed TTV data, we place upper limits on the mass of the hypothetical additional planet as a function of the period ratio of the two planets (WASP-5b and the secondary body) by numerical three-body simulations, in the same manner as presented in several previous analyses (e.g., Steffen & Agol 2005; Miller-Ricci et al. 2008a, 2008b; Bean 2009; Gibson et al. 2009, 2010; Adams et al. 2010; Hrudková et al. 2010).

In order to simplify things, we assume that the secondary planet orbits in the same plane as WASP-5b (the primary planet) and that the two planets have initially circular orbits. Because the amplitude of the timing variations tends to increase as the orbital eccentricity of the second planet increases, basically we only need to consider an initially circular orbit for the secondary planet (e.g., Gibson et al. 2010). For a given initial orbital period, mass ($M_2$), and initial phase ($\theta_2$) of the secondary planet, we performed numerical integrations of the equations of motion for the three-body system using the 4th-order Runge–Kutta method and a time step of 1 s. We continued the integrations for an equivalent elapsed time of 3000 d, which is three times longer than the observation time interval. When the primary planet in the numerical procedure passed through the star–observer field of view, the time step was reduced to 0.001 s, and the calculations were used to create simulated transit timing data. These data were fitted to a linear function in order to obtain an “observed” orbital period and synthetic TTV data, which were then compared to the observed TTV data and a $\chi^2$ value obtained. Transit timings of the secondary planet were also extracted in order to calculate its observed orbital period.

For a given secondary-planet model (initial period ratio, mass, and phase), a $\chi^2$ value was chosen so as to be a minimum by shifting the reference epoch of the artificial TTV data sequentially. We also assumed that the TTV amplitude was proportional to $M_2$ (Agol et al. 2005; Holman & Murray 2005) and integrated only the case of $M_2 = 3 \times 10^{-6}$ $M_\odot$ for each initial period ratio (ranging from 0.2 to 5.0, increased by a factor of 1.005) and $\theta_2$ (stepped by 30°), and then rescaled $M_2$ (or the amplitudes of the artificial TTV data) so that the $\Delta \chi^2$, between the $\chi^2$ value derived above and a $\chi^2$ value for linear fit, became 9.0 ($3 \sigma$ confidence limits).

To check the long-term stability, we also conducted long-term runs for up to 10$^5$ yr with a time step of 100 s, and eliminated models in the cases where the system becomes unstable (one body is ejected or two bodies collide). We then derived 12 upper-limit values of $M_2$ from 12 models of $\theta_2$ as a function of the observed period ratio, and derived a maximum upper-limit value by taking a maximum value for a given period ratio from the linearly interpolated upper-limit lines.

The derived $3 \sigma$ upper limits are shown in figure 5 (black solid line). The overplotted thick-dashed line represents the boundary of the Hill-stable regions calculated by Barnes and Greenberg (2006). We also overplotted an upper-limit line estimated from the RV data (dotted line), which corresponds to a line causing an RV amplitude of 21 m s$^{-1}$; we assumed that the added systematic error of 7 m s$^{-1}$ was entirely due to the possible additional body, and multiplied this value by three, setting an upper limit. As a result, outside the boundaries, we placed upper limits on the secondary mass of 22–70 $M_\oplus$ in the period ratio ranging from 0.2 to 5.0 from the RV data, and more stringent limits down to 2 $M_\oplus$ near 1:2 and 2:1 MMRs from the TTV data (at the $3 \sigma$ level).

We also put an upper limit on the mass of a Trojan companion (an object at one of the two triangular Lagrange points, L4 and L5, of the planet–star orbit) as 100 $M_\oplus$ ($3 \sigma$) from the TTV data. The upper limit of $\sim 40 M_\oplus$ at 1:1 MMR from the RV data is not correct, because if a Trojan companion exists at L4 or L5 point, the observed RV data would show one planet orbiting at the barycenter of the primary planet and the

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**Table 9.** Expected TTVs for WASP-5b induced by effects other than that of an additional perturbing planet or Trojan.*

| Effect                                | Expected TTVs | References |
|---------------------------------------|---------------|------------|
| The Appregate effect                  | $\sim 1.5$ ($T_{mod}/11$ yr) [s] | Watson and Marsh (2010) |
| Light travel time effect              | $\leq 1$ [s/3 yr]$^\dagger$ | e.g., Agol et al. (2005) |
| Exomoon                               | $\leq 20$ [ms] | Kipping (2009); Weidner and Horne (2010) |
| Tidal dissipation                     | $\sim 5$ [ms yr$^{-1}]^\ddagger$ | Hellier et al. (2009) |
| Orbital precessions due to ...        |               |            |
| tidal deformations                    | $< 130$ [ms yr$^{-1}]$|$^\ddagger$ | Heyl and Gladman (2007); Jordán and Bakos (2008) |
| general relativistic effect           | $< 2$ [ms yr$^{-1}]$ | Heyl and Gladman (2007); Jordán and Bakos (2008) |
| stellar quadrupole moment            | $< 0.004$ [ms yr$^{-1}]$|$^\ddagger$ | Heyl and Gladman (2007); Jordán and Bakos (2008) |

* $T_{mod}$ denotes the modulation time-scale of the host star.
† The case having a Jovian-mass secondary planet with an orbital period of $\sim 3$ yr, which corresponds to the actual observational period. This produces the RV amplitude of $\sim 21$ m s$^{-1}$ which corresponds to the upper limit placed from the RV data.
‡ An adopted value estimated for OGLE-TR-56b, whose properties are similar to those of the WASP-5b system, as an approximation.
§ Equations (5), (1), and (3) of Jordán and Bakos (2008) are used for calculating precession rates due to tidal deformations, the general relativistic effect, and stellar quadrupole moment, respectively, and an equation (23) of Heyl and Gladman (2007) into which the rates are substituted is used for calculating the transit timing delays. Eccentricity of the primary planet of 0.032 is adopted which is 3$\sigma$ upper limit derived in this work.
Fig. 5. Estimated 3σ upper limits on mass of the hypothetical secondary planet as a function of the orbital-period ratio (black solid line), assuming two planets are coplaner and have initially circular orbits. The blue dotted line represents upper limits on the secondary mass estimated from the RV data, which corresponds to a line causing the RV amplitude of 21 m s⁻¹ due to the secondary body. The green dashed line shows a boundary of Hill-stable region calculated from Barnes and Greenberg (2006). Gray vertical-dashed lines represent corresponding MMRs.

Trojan companion. Instead, a method for finding an imbalance of mass at the L4/L5 points using both RV and photometric data has been proposed by Ford and Gaudi (2006). The basic idea of this method is to observe a difference between the time of vanishing stellar RV variation (T₀;RV) and the time of the midtransit (T₁;0), Madhusudhan and Winn (2009) estimated the upper mass of the imbalance mass of Trojan companions in the WASP-5 system as < 54.7 M⊕ (2σ) at the L5 point (behind the planet), based on the data of A08. Here, we improved this estimate employing more RV and photometric data. We measured the time difference, Δt = T₁;0 - T₀;RV, with (without) RV data during transit (14 data points), adopting an eccentricity of WASP-5b of zero, resulting in Δt = 4.8 ±/− 4.4 min (12.8 ±/− 4.8 min). Accordingly, we set upper limits on the excess mass of the Trojan companions, M_T, which is defined as the difference in the mass at L4 (M_T,L4) and the mass at L5 (M_T,L5) (namely, M_T ≡ M_T,L4 - M_T,L5), through the relation

\[ M_T = M_p \left( \frac{2 \tan(2\pi \Delta t / P)}{\sqrt{3} - |\tan(2\pi \Delta t / P)|} \right), \]  

(8)

where P and M_p are the orbital period and mass of WASP-5b, respectively [equation (2) in Madhusudhan & Winn (2009) and originally from equation (1) in Ford & Gaudi (2006)]. We found M_T = 7.4 ± 6.8 (19.8 ± 7.7) M⊕ and put an upper limit on the excess mass near the L4 point of ~ 28 M⊕ (~ 43 M⊕) at the 3σ level. This result lowered the limit derived from only the TTV data (< 100 M⊕), and improved that derived by Madhusudhan and Winn (2009) by at least a factor 2.

4.3. Example Models of Secondary Planet

Here, in order to illustrate example models of a secondary planet that can account for the observed timing variations, we fit the simulated TTV data to the observed one, and searched for well-fitting models. Using the artificial TTV data generated in the previous section, in which the initial eccentricity of the secondary planet, e₂, was set to zero, we searched for a best-fit solution for each orbital period ratio by scaling the TTV amplitude and shifting a reference epoch of the artificial TTV data. At this time, we used only the case that the initial phase of the secondary planet is zero for the sake of simplicity. Since, generally, a libration period of TTVs increases as the orbital period ratio approaches to an MMR, solutions around MMRs should be searched finely. For this reason, we generated a set of additional artificial TTV data around low-order MMRs of 1:4, 1:3, 1:2, 2:3, 1:2, 5:3, 2:1, 3:1, and 4:1, by 10 times denser than the other regions, and also searched for best-fit solutions for the additional period ratios. We then converted the best-fit TTV amplitudes to the secondary masses, assuming that a TTV amplitude is proportional to a secondary-planet mass. In addition to the case of e₂ = 0, we also generated a set of artificial TTV data for the case of e₂ = 0.1 under the same conditions as the previous one and in an additional condition: the initial phase of the periapsis of the secondary planet, which was set to zero. In this case, the regions around the MMRs of 1:4, 1:3, 2:5, 1:2, 3:5, 2:1, 5:2, 3:1, and 4:1 are searched densely. We then searched for the best-fit solutions against the respective
Fig. 6. Best-fit mass regions of the hypothetical secondary planet as a function of the orbital period ratio (thin-solid lines in upper panels) and their $\chi^2$ values (lower panels), for the cases of $e_2 = 0$ (left) and 0.1 (right). The gray thick lines are the same as the black line in figure 5. The locations of four example TTV models shown in figure 8 are marked as star symbols and alphabets of (a), (b), (c), and (d).

Fig. 7. Enlarged parts around the 2:1 MMR of figure 6. Discontinuous features are seen in the vicinity of the 2:1 MMR because the strong resonance near the MMR much excites the orbital eccentricities of the two planets, which results in the jumps at certain “observed” period-ratios.

orbital period ratios. Figure 6 shows the derived best-fit mass of the secondary planet as a function of the orbital period ratio for the cases of $e_2 = 0$ (left top panel) and $e_2 = 0.1$ (right top panel), and their $\chi^2$ values (bottom panels).

As a result, for the case of $e_2 = 0$, the regions where the best-fit masses are lower than the upper limits placed from the radial velocity data (RV limits) are limited only around the low-order MMRs of 1:3, 1:2, 3:5, 5:3, 2:1, and 3:1. Such regions then extend to around other MMRs as $e_2$ increases to 0.1. In addition, the $\chi^2$ maps show that there are a number of local minima over the period-ratio range, reflecting the fact that the libration period of artificial TTVs gradually changes as the orbital period ratio changes, and some of the local minima around MMRs have low-$\chi^2$ values, less than degrees of freedom of 9. Figure 7 shows the enlarged around the 2:1 MMR for example. These facts suggest that it is possible to explain the observed TTV data by a certain model of a perturbing planet having lower mass than the RV limit, and such a model would be likely near low-order MMRs, if its eccentricity is small enough. Non- or a small eccentricity of the secondary planet is naturally expected if the planet has migrated with interaction between disk and planet, and if the above scenario is true this fact could be important observational evidence that the hot Jupiter has been formed according to one of the disk-planet
Fig. 8. Four example TTV models (solid curves) with the observed TTV data (legends are the same as in figure 4) (top panels) and their residuals (bottom panels). The explanations for these models appear in the text.

interaction models (e.g., Thommes 2005). This would also be consistent with the fact that the sky-projected spin–orbit angle is consistent with zero.

We show four example TTV models (a, b, c, and d), having lower masses than the RV limits and located near MMRs, with the observed TTVs in figure 8. The locations in parameter space of the period ratio and the mass are marked as star symbols in figure 6: (a) is the least $\chi^2$ model ($\chi^2 = 4.35$) in all models considered here, which is located near the 1:2 MMR and 0.003 $M_{\text{jup}}$ in the case of $e_2 = 0$; (b) is a low-$\chi^2$ model ($\chi^2 = 5.01$) located near the 2:1 MMR and 0.093 $M_{\text{jup}}$ in the case of $e_2 = 0$. Since (a) and (b) show similar libration periods and amplitudes, it would be difficult to distinguish between those by only ground-based TTV observations. Radial velocity follow-up observations would be necessary, if one of such models is true. And (c) is another low-$\chi^2$ model ($\chi^2 = 6.65$) located near the 2:1 MMR and 0.011 $M_{\text{jup}}$ in the case of $e_2 = 0$; (d) is a model located near the 4:1 MMR and 0.053 $M_{\text{jup}}$ in the case of $e_2 = 0.1$ with $\chi^2 = 20.57$. The $\chi^2$ value of model (d) is somewhat high due to the relatively longer libration period; however, if the two timing data having the largest error bars ($E = 7$ and 451) are discarded, the $\chi^2$ value decreases to 11.6 for 7 degrees of freedom, and therefore such longer libration-period model is also thinkable.

On the other hand, a non-MMR models with rather higher eccentricity might also be possible, for which we do not search here. If this case is true, it would be the first example where a hot-Jupiter system has a non-MMR, low-mass planet with a short orbit. Recently, it has been revealed that most multi-planetary systems consisting of several hot super-Earths are not in MMRs (Mayor et al. 2009a, 2009b) and this cannot be explained naturally by using standard migration models.
(Terquem & Papaloizou 2007; Ogihara et al. 2010). Thus, it is important to check whether the situations in hot-Jupiter systems are the same or not.

In order to distinguish between these models, and to find an exclusive solution, additional high-precision and extensive timing data are necessary, and follow-up observations of the high-precision radial velocity are also helpful in confirming the additional planetary signal and constrain the physical parameters. A successful program would provide valuable information on our understandings of planetary formation scenarios.

5. Summary

We have observed 7 new transits of the hot Jupiter WASP-5b using a 61 cm telescope in order to search for an additional body via the TTV method. By combining them with all available photometric and RV data, we slightly refined the transit-model parameters and confirmed that all parameters were consistent with published values, except for the orbital period, which may be a sign of TTV. We also confirmed that the sky-projected spin–orbit angle is consistent with zero, which was first reported by Triaud et al. (2010), including independent photometric data and using an improved RM formula. This fact is consistent with a disk–planet interaction model being the favored migration scenario for WASP-5b, although planet–planet scattering models cannot be excluded at this point in time.

The $\chi^2$ value for a linear fit to the 11 transit timings is 32.2 for 9 degrees of freedom. This result indicates that the transit timings do not match a linear ephemeris at a confidence level of 99.982%, or 3.7σ, either due to unknown systematic effects, or possibly due to real TTVs. If this signal is real, the standard deviation of the TTVs is as large as 50σ, and most likely cause is the presence of an additional body in the system. From the RV data, we put an upper limit on the RV amplitude caused by the possible secondary body (planet) as 21 m s$^{-1}$, which corresponds to its mass of 22–70 $M_\oplus$ over the orbital period ratio of the two planets ranging from 0.2 to 5.0. From the RV data, using numerical simulations, we place more stringent limits down to 2 $M_\oplus$ near the 1:2 and 2:1 MMRs with WASP-5b at the 3σ level, assuming that the two planets are coplanar. We also put an upper limit on the excess Trojan mass, 43 $M_\oplus$ (3σ), using both RV and photometric data.

We also found that if the possible secondary planet has non- or a small eccentricity, it would be likely near low-order MMRs. This fact would also support the disk–planet interaction models as the migration mechanisms for the hot Jupiter. Alternatively, if the secondary body is an eccentric, non-MMR planet, it would be a challenge for the current planetary migration models. Further follow-up observations for the WASP-5 system both photometrically and spectroscopically will reveal the true nature of the TTV signal and shed light on the migration mechanisms of planetary systems.

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Appendix. Light Curve Correction Factor

When we consider primary and secondary atmospheric extinctions, time-averaged standard magnitudes of a target star and a reference star in an arbitrary passband, $M_{\text{obj}}$ and $M_{\text{ref}}$, can be expressed as:

\[
M_{\text{obj}} = m_{\text{obj}} - k' z - k'' C_{\text{obj}} z + T C_{\text{obj}} + Z_p + f_{\text{obj}}(t),
\]

(A1)

\[
M_{\text{ref}} = m_{\text{ref}} - k' z - k'' C_{\text{ref}} z + T C_{\text{ref}} + Z_p + f_{\text{ref}}(t),
\]

(A2)

where $m_{\text{obj}}$ and $m_{\text{ref}}$ are observed magnitudes of the target star and the reference star; $C_{\text{obj}}$ and $C_{\text{ref}}$ are their color indices, $z$ is the airmass, $T$ is the transformation factor, $Z_p$ is the nightly zero point, $k'$ and $k''$ are coefficients of primary and secondary extinctions, and $f_{\text{obj}}(t)$ and $f_{\text{ref}}(t)$ are terms of stellar intrinsic variability as a function of time (see, e.g., Chapter 6 of Warner 2006).

When we approximate each stellar intrinsic brightness that varies with time in linear function, then the difference in magnitude between the target star and the reference star, $\Delta M = M_{\text{obs}} - M_{\text{ref}}$, is written as

\[
\Delta M = \Delta m - k'' \Delta C z + T \Delta C + a t + b,
\]

(A3)

where $\Delta m = m_{\text{obj}} - m_{\text{ref}}$, $\Delta C = C_{\text{obj}} - C_{\text{ref}}$, and $a$ and $b$ are coefficients. Here, we assume that $k''$ varies with time $t$ in linear function, as $k'' = k''_0 + k''_1 t$; then,

\[
\Delta M = \Delta m - (k''_0 + k''_1 t) \Delta C z + T \Delta C + a t + b.
\]

(A4)

Consequently, if we redefine $k_0 \equiv -k''_0 \Delta C$, $k_1 \equiv -k''_1 \Delta C$, $k_t \equiv a$, and $k_0 \equiv T \Delta C + b$, the correction magnitude, $\Delta m_{\text{corr}} = \Delta M - \Delta m$, can be written as

\[
\Delta m_{\text{corr}} = k_0 z + k_1 t z + k_t t + k_0.
\]

(A5)
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