POSSIBLE TRANSIT TIMING VARIATIONS OF THE TrES-3 PLANETARY SYSTEM

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ABSTRACT

Five newly observed transit light curves of the TrES-3 planetary system are presented. Together with other light-curve data from the literature, 23 transit light curves in total, which cover an overall timescale of 911 epochs, have been analyzed through a standard procedure. From these observational data, the system’s orbital parameters are determined and possible transit timing variations (TTVs) are investigated. Given that a null TTV produces a fit with reduced $\chi^2 = 1.52$, our results agree with previous work, that TTVs might not exist in these data. However, a one-frequency oscillating TTV model, giving a fit with a reduced $\chi^2 = 0.93$, does possess a statistically higher probability. It is thus concluded that future observations and dynamical simulations for this planetary system will be very important.

Key words: planetary systems – stars: individual (TrES-3) – techniques: photometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The development of research in extra-solar planetary systems has been successful for nearly two decades. In addition to the steadily increasing number of newly detected systems, many new discoveries of planetary properties also make this field extremely exciting. The Doppler-shift method has made many extra-solar planetary systems known to us. The methods of transit, micro-lensing and direct imaging, have also produced fruitful results. In particular, more than 100 extra-solar planets (exoplanets) have been found to transit their host stars. Recently, based on the transit method, the Kepler space telescope has revealed many interesting results. For example, one of the greatest achievements is the discovery of a system with six planets (Lissauer et al. 2011). These results truly demonstrate the state-of-the-art power of the transit technique.

Among these detected planetary systems, TrES-3 (O’Donovan et al. 2007) attracts much attention due to its strong transit signal and short orbital period. For example, Sozzetti et al. (2009) presented a work which combines the data from spectroscopic and photometric observations of TrES-3 to obtain the best models for the host star and planet. On the other hand, Fressin et al. (2010) used the Spitzer Space Telescope to monitor TrES-3 during its secondary eclipse. The most important constraint from these results is to show that the orbital eccentricity is very small, i.e., $|e \cos(\omega)| < 0.0056$, where $e$ is the orbital eccentricity and $\omega$ is the longitude of the periastron. Furthermore, the 10.4 m Gran Telescopio Canarias (GTC; currently the world’s largest optical telescope) has obtained extremely high-precision narrowband transit data for the TrES-3 system (Colón et al. 2010). There is almost no deviation for the data on the light curve, so this data could show a strong constraint on orbital parameters of the exoplanet TrES-3b.

In order to study the perturbation from small unknown planets and to constrain the overall orbital configuration in planetary systems, transit timing variations (TTVs) have been seriously investigated in recent years (Agol et al. 2005; Holman & Murray 2005). Some of these works find that there is no TTV for the systems they studied. For example, Miller-Ricci et al. (2008) showed that there is no TTV signal above 80 s in the HD209458 system. Winn et al. (2009) also failed to confirm any TTVs for the WASP-4 system. In contrast, Maciejewski et al. (2010) reported a successful case where a periodical TTV was found and which was likely due to an additional 15 Earth-mass planet located near the outer 1:2 mean-motion resonance in the WASP-3 system. Moreover, Holman et al. (2010) confirmed TTVs in the double transiting planetary system Kepler-9.

For the TrES-3 system, there are also many studies on TTV measurements. In addition to providing the best model for the central star and planet, Sozzetti et al. (2009) also found that the timing data gives a reduced $\chi^2$ of about 5.87 with the assumption of no TTVs. The authors concluded that there could be two possibilities: (1) the period is not a constant, thus indicating some level of TTVs; or (2) the error bars might have been underestimated. Gibson et al. (2009) showed that the reduced $\chi^2$ is 2.34 when the period is set to be a constant. They also used the data to set the mass limit of the additional planet. Finally, Maciejewski et al. (2011) obtained a reduced $\chi^2$ of about 2.48 for a linear fit with a constant period.

These results imply that further studies are necessary to address the significance of TTVs and explore a possible dynamical interpretation. Thus, in this paper, we plan to perform further investigations for the TrES-3 system through a self-consistent procedure with both newly obtained observational data and data from published papers. It is the first time for the TrES-3 planetary system when 23 light curves, which cover a timescale of 911 epochs, are employed to determine orbital parameters and mid-transit times through a uniform procedure. The observational results are presented in Section 2, the analysis of light curves is shown in Section 3, the comparisons with previous
Figure 1. Left panels: the normalized relative flux as a function of the time (the offset from mid-transit time and in TDB-based BJD) of five transit light curves in this work: points are the data and curves are models. Right panels: the corresponding residuals. From top to bottom: our observational data of Runs 1–5 listed in Table 1.

works are in Section 4, the possible TTV frequencies and models are discussed in Section 5, and finally the conclusions are presented in Section 6.

2. OBSERVATIONAL DATA

2.1. Observations and Data Reduction

In this project, we monitor the TrES-3 system with the 0.8 m telescope at Tenagra Observatory in Arizona, USA. In 2010 May and June, five runs of transit observations were successfully completed by our group. For all these observations, the $R$ band was chosen and the exposure time was set to 100 s. The field of view was 14.8 arcmin by 14.8 arcmin, giving a scale of 0.87 arcsec pixel$^{-1}$. The images had a typical FWHM of 2.5 pixels. A summary of the observations is presented in Table 1.

Using the standard IRAF software, images were first debiased and flat-fielded, and then the differential photometry was performed. We searched for nearby bright stars with known identities to be the candidates for comparison stars. There were four candidates, but two of them were not suitable due to the observed stellar flux being saturated or being variable. Thus, we finally used the star TYC3089-883-1 and the star TYC3089-1137-1 as our comparison stars. The flux of TrES-3 was divided by the flux of each comparison star, and also divided by the sum of the flux from both stars, to obtain three light curves. The one with the smallest out-of-transit root mean square (oot rms) was used as the TrES-3 light curve for each transit event. The values of the oot rms of five transit light curves are listed in Table 1, which quantify the quality of the light curves. The normalized relative flux and residuals as a function of the time of five transit light curves obtained from our observations are shown in Figure 1.

2.2. Other Observational Data from Literature

Eight light curves from Sozzetti et al. (2009), nine light curves from Gibson et al. (2009), and the transit data from Colon et al. (2010), which employed the 10.4 m telescope GTC are included in our analysis. Please note that we do not simply use the mid-transit times written in these papers, but analyze photometric data with the same procedure and software to perform parameter fitting in a consistent way. This approach is a better procedure for studying possible TTVs when different sources of data are considered.

3. THE ANALYSIS OF LIGHT CURVES

The Transit Analysis Package (TAP) described by Gazak et al. (2012) was used for our light-curve analysis. In addition to Gazak et al. (2012), Fulton et al. (2011) also presented the procedure of using TAP in their study of a HAT-P-13 system. The Markov Chain Monte Carlo (MCMC) technique and the
model from Mandel & Agol (2002) were employed to fit the light curves in TAP. A description for other details of techniques about TAP can be found in the study by Fulton et al. (2011).

Mandel & Agol (2002) provided models of transit light curves derived from a simple two-body star–planet system. TAP can thus determine the best two-body orbital model from the observational data. In order to detect possible changes in orbital parameters, we analyzed individual epochs separately.

Before using TAP, the target’s flux was normalized so that the out-of-transit flux values were close to unity. Moreover, as described in Eastman et al. (2010), the Barycentric Julian Date (BJD) with the time standard Barycentric Dynamical Time (TDB), i.e., TDB-based BJD, was used for the time stamps in light curves here.

These light-curve data were then loaded into TAP to start MCMC chains. For each light curve, five chains of length 300,000 were computed. To start an MCMC chain in TAP, we needed to set the initial values of the following parameters: orbital period $P$, orbital inclination $i$, semimajor axis $a$ (in the unit of stellar radius $R_*$), the planet’s radius $R_p$ (in the unit of stellar radius), the mid-transit time $T_{\text{trans}}$, the linear limb-darkening coefficient $u_1$, the quadratic limb-darkening coefficient $u_2$, orbital eccentricity $e$, and the longitude of periastron $\omega$. Once the above initial values were set, one could choose any one of the above to be (1) completely fixed; (2) completely free to vary; or (3) varying following a Gaussian function, i.e., Gaussian prior, during the MCMC chain in TAP.

We analyzed each light curve through TAP separately and, thus, the orbital period was treated as a fixed parameter. The value of the orbital period in Sozzetti et al. (2009) was adopted. Because the orbital period is fixed, the semimajor axis shall not be completely free to vary. Thus, a Gaussian prior centered on the value 5.926 with $\sigma = 0.056$ was set for $a/R_*$ during TAP runs, where both the central value and the error bar were taken from Sozzetti et al. (2009).

Moreover, $e$ and $\omega$ are simply fixed to be zero, and $i$ is treated in the same way as the semimajor axis. We leave the mid-transit times $T_{\text{m}}$ and $R_p/R_*$ to be completely free during TAP runs and obtain their best values for each light curve. They are the main parameters we would like to obtain through light-curve data.

For the limb-darkening effect, a quadratic limb-darkening law with coefficients bilinearly interpolated from Claret (2000, 2004) to the values of effective temperature $T_{\text{eff}} = 5650.0$ K, stellar surface gravity log $g = 4.40$ cm s$^{-2}$, metallicity $[\text{M}/\text{H}] = -0.2$, and micro-turbulent velocity $V_t = 2.0$ km s$^{-1}$ is adopted, as in Sozzetti et al. (2009). Thus, the limb-darkening coefficients are treated as prior parameters. However, Southworth (2008) found that the difference between the best-fitted limb-darkening coefficients and those theoretical values interpolated from Claret (2000, 2004) could be about 0.1 or 0.2. Thus, in order to take this possible difference into account, a Gaussian prior centered on the theoretical values with $\sigma = 0.05$ is set for limb-darkening coefficients $u_1$ and $u_2$ during TAP runs, where the value $\sigma = 0.05$ is taken as half of 0.1 and could make the Gaussian distribution’s full width include possible differences. The details of parameter setting for TAP runs are listed in Table 2.

The limb-darkening coefficients are dependent on the filters employed during observations. Table 3 lists these theoretical limb-darkening coefficients $u_1$ and $u_2$ for all bands considered in this paper. In any TAP run, these theoretical values are used as the initial $u_1$ and $u_2$, and also as the central values of Gaussian priors. However, the nine RISE light curves in Gibson et al. (2009) were obtained through a special instrument with a single non-standard wide-band filter covering $V$ and $R$ bands. The average values for filters $V$ and $R$ in Table 3 were used as the theoretical limb-darkening coefficients $u_1$ and $u_2$ when we ran TAP for these light curves. Moreover, in Colon et al. (2010), two narrow near-infrared bands at 790.2 nm and 794.4 nm are used to obtain high-precision transit data. There are 36 data points at 790.2 nm and 35 data points at 794.4 nm, so in total 71 data points are used for one transit event. Since these two wavelengths are very close and are at the center of the $I$ band, the
Table 4
The Results of Light-curve Analysis for $T_m$, $i$, and $a/R_*$

| Epoch | Data Source | $T_m$ (deg) | $a/R_*$ |
|-------|-------------|-------------|----------|
| 0     | (a) 4115.9111 | 81.90±0.10 | 5.906±0.043 |
| 10    | (a) 4198.9735 | 81.79±0.14 | 5.944±0.052 |
| 22    | (b) 4214.6469 | 81.81±0.12 | 5.915±0.046 |
| 23    | (b) 4215.9259 | 81.77±0.12 | 5.937±0.047 |
| 267   | (b) 5343.6631 | 81.79±0.12 | 5.952±0.044 |
| 268   | (a) 5353.9690 | 81.83±0.12 | 5.920±0.047 |
| 269   | (b) 5452.9496 | 81.86±0.11 | 5.939±0.043 |
| 294   | (b) 5469.9282 | 81.82±0.12 | 5.926±0.047 |
| 313   | (b) 4594.7468 | 81.85±0.13 | 5.943±0.047 |
| 329   | (b) 4615.6461 | 81.81±0.11 | 5.915±0.044 |
| 342   | (b) 4632.6290 | 81.81±0.11 | 5.937±0.042 |
| 355   | (b) 4649.6712 | 81.81±0.11 | 5.931±0.042 |
| 358   | (b) 4653.5261 | 81.89±0.14 | 5.913±0.052 |
| 365   | (b) 4662.6698 | 81.90±0.13 | 5.915±0.052 |
| 371   | (b) 4670.7070 | 81.86±0.11 | 5.885±0.046 |
| 374   | (b) 4674.4251 | 81.74±0.12 | 5.965±0.047 |
| 381   | (b) 4683.5612 | 81.85±0.13 | 5.927±0.048 |
| 665   | (c) 5054.5252 | 81.83±0.10 | 5.932±0.043 |
| 885   | (d) 5341.8838 | 81.81±0.15 | 5.935±0.053 |
| 898   | (d) 5358.8669 | 81.75±0.14 | 5.957±0.053 |
| 901   | (d) 5362.7847 | 81.83±0.15 | 5.937±0.053 |
| 904   | (d) 5366.7021 | 81.95±0.14 | 5.987±0.052 |
| 911   | (d) 5375.8467 | 81.89±0.14 | 5.912±0.052 |

Notes: Data sources: (a) Sozzetti et al. (2009), (b) Gibson et al. (2009), (c) Colon et al. (2010), and (d) this work. To save space, the value of the mid-transit time $T_m$ (in TDB-based BJD) is subtracted by 2,450,000.

$u_1$ and $u_2$ for filter $I$, shown in Table 3, were used as the theoretical limb-darkening coefficients.

All results derived through TAP are shown in Tables 4 and 5. The first TrES-3 transit in Sozzetti et al. (2009) is defined as epoch $E = 0$, and other transits' epochs are defined accordingly. These two tables list all parameter values with uncertainties following the order of epochs. Moreover, the observational light curves and best-fitting models of our own data are presented in Figure 1, where the points are observational data and solid curves are the best-fitting models. The original data points in Figure 1 are available in a machine-readable form in the online journal in Table 6.

For a photometric light curve, there are two possible sources of error. The uncorrelated Gaussian scatter is called “white noise,” and the time-correlated Gaussian scatter is “red noise.” TAP is designed to decompose and model the above two sources of error with the technique of wavelet analysis.

The error bars of orbital parameters and mid-transit times shown in Table 4 are the results of our TAP runs. There are five chains in each of our TAP runs, and all of the chains are added together into the final results. The 15.9, 50.0, and 84.1 percentile levels are recorded. The 50.0 percentile, i.e., median level, is used as the best value, and the other two percentile levels give the error bar.

This error analysis was tested and shown to be successful in Gazak et al. (2012). Moreover, we found that when the deviations of transit-light-curve data are smaller, the resulting error bars become smaller. Thus, the error bar does reflect the quality of the data. The MCMC procedure in TAP gives a reasonable estimation of the error related to the data itself. Therefore, the error bars we obtained here should have been consistent with the scattering and quality of the light curves, and provide reliable error estimates.

4. COMPARISON WITH PREVIOUS STUDIES

Gibson et al. (2009) presented the results of transit timing residuals in their Figure 3, where both the data in Gibson
et al. (2009) and Sozzetti et al. (2009) are included. Tables 3 and 4 in Gibson et al. (2009) provide the values of mid-transit times in HJD for all of their nine transit light curves and also for those eight light curves from Sozzetti et al. (2009). After converting these values from HJD to TDB-based BJD and adopting their values of uncertainties, an ephemeris is calculated by minimizing $\chi^2$ through fitting a linear function:

$$T^C_m(E) = PE + T^C_m(0),$$

(1)

where $P$ is the orbital period, $E$ is an epoch, $T^C_m(E)$ is the calculated mid-transit time at a given epoch $E$, and so $T^C_m(0)$ is the value for $E = 0$. We found that $P = 1.30618631 \pm 0.00000016$, $T^C_m(0) = 2454185.91111514 \pm 0.00005033$, and the corresponding $\chi^2 = 34.26$. Since the degree of freedom is 15, the reduced $\chi^2 = 2.28$. The $O-C$ diagram, which shows the differences between the observational mid-transit time and the calculated mid-transit time of a simple two-body star–planet system (i.e., $T_m - T^C_m$) as a function of epoch $E$, is shown in the top panel of Figure 2.

On the other hand, as we mentioned in Section 3, we also have the mid-transit times directly derived from the light curves in the studies of Sozzetti et al. (2009) and Gibson et al. (2009) as shown.
in Table 4. Similarly, by minimizing $\chi^2$ through fitting a linear function as in Equation (1), it was found that $P = 1.30618691 \pm 0.00000051$, $T_m^C(0) = 2454185.91099199 \pm 0.00015123$, and the corresponding $\chi^2 = 19.69$. As the degree of freedom is 15, the reduced $\chi^2 = 1.31$. Thus, another $O-C$ diagram can be plotted as in the bottom panel of Figure 2.

From both panels in Figure 2 and the resulting ephemeris, we see that what we derived directly from the light curves is correct. Our error bars are larger than those in the previous work, so that the value of $\chi^2$ is smaller. Therefore, the error bars are unlikely to be underestimated in our results presented in this paper.

5. TRANSIT TIMING VARIATIONS

5.1. A New Ephemeris

When all 23 light curves mentioned in Section 2 are considered, we obtain a new ephemeris by minimizing $\chi^2$ through fitting a linear function as in Equation (1). We find that $P = 1.30618619 \pm 0.00000015 = P_l \pm 0.00000015$, where $P_l \equiv 1.30618619$, $T_m^C(0) = 2454185.91116430 \pm 0.00006123 = T_l \pm 0.00006123$, and the corresponding $\chi^2 = 31.95$. Because the degree of freedom is 21, the reduced $\chi^2 = 1.52$. Using this new ephemeris, the $O-C$ diagram is shown in Figure 3.
Therefore, for a straight line fit, i.e., a null-TTV model, our reduced \( \chi^2 \) with all 23 light curves considered is smaller than the value of 2.34 from Gibson et al. (2009). This could be partially due to error bars being slightly larger here than those in Gibson et al. (2009). Therefore, our error bars are underestimated, and are unlikely to lead to a result with false-positive TTVs.

5.2. The Frequency Analysis and Possible Models

In order to investigate whether there are any TTVs, Lomb’s normalized periodogram (Press et al. 1992) was used to search for possible variations in the data. Figure 4 shows the resulting spectral power as a function of frequencies. We defined the frequency with largest power as \( f_1 \), i.e., \( f_1 \equiv 0.01055 \), and tested the possible TTVs with frequency \( f_1 \) by minimizing \( \chi^2 \) through fitting a function

\[
T_S(E) = PE + b + a \sin(2\pi f_1 E - \phi_1),
\]

where \( T_S(E) \) is the predicted mid-transit time at a given epoch \( E \) and \( b, a, \phi_1 \) are fitting parameters. We obtained that \( P = 1.30618631 \pm 0.00000031, b = 2454185.91100290 \pm 0.00012187, a = 0.00036500 \pm 0.00009570, \) and \( \phi_1 = 3.97482109 \pm 0.25632765 \). The corresponding \( \chi^2 = 17.59 \). Since the degree of freedom is 19, the reduced \( \chi^2 = 0.93 \).

Using the above best-fitted parameters for \( T_S(E) \) and the new ephemeris \( P_i, T_i \) for \( T_m(E) \), the curve \( T_S(E) - T_m(E) \) as a function of epoch \( E \) is plotted in the \( O-C \) diagram, together with data points, as shown in Figure 5.

In order to test the models with multiple frequencies, the frequency with the \( i \)th highest power is defined as \( f_i \), where \( i = 2, \ldots, 5 \). Then, possible TTV models with \( N \) frequencies can be tested by minimizing \( \chi^2 \) through fitting a function

\[
T_S(E) = PE + b + a_N \sum_{i=1}^{N} \sin(2\pi f_i E - \phi_i),
\]

where \( N = 2, \ldots, 5 \). These results of multiple frequencies, together with the results of null-TTV and one-frequency TTV models, are all summarized in Table 7. Similarly, employing the best-fitted parameters for \( T_S(E) \) and the new ephemeris \( P_i, T_i \) for \( T_m(E) \), the curves \( T_S(E) - T_m(E) \) as a function of epoch \( E \) are shown in the \( O-C \) diagram, together with data points, as in Figures 6(A)–(D).

From the values of reduced \( \chi^2 \) presented in Table 7, it is clear that the model with one frequency, i.e., the one-frequency model, has the highest probability of producing the possible TTVs implied by the observational data. In fact, one-frequency, two-frequency, three-frequency, and four-frequency models are all better than the null-TTV model as their reduced \( \chi^2 \) is closer to unity. Among these, the curve of the three-frequency model almost goes through the error bars of all the points. Due to the overfitting, the reduced \( \chi^2 \) of the five-frequency model is very small.

6. CONCLUDING REMARKS

In this paper, five new transit light curves and others from the literature, including one from Colon et al. (2010), eight from Sozzetti et al. (2009), and another nine from Gibson et al. (2009), are employed to obtain the orbital parameters of the TrES-3 planetary system. These 23 transit light curves, which cover an overall timescale of 911 epochs, have been analyzed.

![Figure 6. i-frequency model and the O-C diagram, where i = 2, 3, 4, and 5 ((A)–(D)). The curve is for the fitting function. The filled circles are for this work, squares are for the data from Sozzetti et al. (2009), the filled triangle is for 10.4 m GTC data, and crosses are for the data from Gibson et al. (2009).](image)
Table 7
The Values of Fitted Parameters, Degree of Freedom, Reduced $\chi^2$ of the Null-TTV Model, and $i$-frequency Models, where $i = 1, 2, \ldots, 5$

| Model           | Fitted Parameters | Degree of Freedom | Reduced $\chi^2$ |
|-----------------|-------------------|-------------------|------------------|
| Null-TTV        | $P = 1.30618619 \pm 0.00000015$, $T_m^{(0)} = 2454185.91116450 \pm 0.00006123$ | 21                | 1.52             |
| One-frequency   | $P = 1.30618631 \pm 0.00000031$ $b = 2454185.91100290 \pm 0.00012187$ $a = 0.00036500 \pm 0.00009570$ $\phi_1 = 3.97482109 \pm 0.25632765$ | 19                | 0.93             |
| Two-frequency   | $P = 1.30618560 \pm 0.00000045$ $b = 2454185.91144686 \pm 0.00016052$ $a = 0.00053559 \pm 0.00018953$ $\phi_1 = 2.46731638 \pm 0.28913521$ $\phi_2 = 5.58758211 \pm 0.31948870$ | 18                | 1.32             |
| Three-frequency | $P = 1.30618619 \pm 0.00000031$ $b = 2454185.9111750 \pm 0.00013402$ $a = 0.00218541 \pm 0.00062400$ $\phi_1 = 0.49000000 \pm 0.30458730$ $\phi_2 = 2.39100003 \pm 0.13629963$ $\phi_3 = 0.01779999 \pm 0.07340797$ | 17                | 0.85             |
| Four-frequency  | $P = 1.30618572 \pm 0.00000036$ $b = 2454185.91134611 \pm 0.00018133$ $a = 0.00142777 \pm 0.00059381$ $\phi_1 = 3.72499990 \pm 0.31527481$ $\phi_2 = 2.39299988 \pm 0.42470514$ $\phi_3 = 2.48769998 \pm 0.42087095$ $\phi_4 = 0.27669999 \pm 0.28758257$ | 16                | 0.86             |
| Five-frequency  | $P = 1.30618596 \pm 0.00000040$ $b = 2454185.91131390 \pm 0.00014342$ $a = -0.00219894 \pm 0.00088575$ $\phi_1 = 3.68168863 \pm 0.36549767$ $\phi_2 = 0.23228741 \pm 0.14950905$ $\phi_3 = 5.53840208 \pm 0.35394611$ $\phi_4 = 2.04820298 \pm 0.34912726$ $\phi_5 = 4.09944880 \pm 0.33490377$ | 15                | 0.64             |

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