Exoplanet Transit Photometry for TESS Planetary Candidates TOI-4439.01 & TOI-5278.01

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ABSTRACT
The Transiting Exoplanet Survey Satellite (TESS) is an all-sky survey mission led by MIT and NASA in search of exoplanets. A certain number of planet candidates (PC) discovered by TESS are not actual transiting exoplanets, which are usually referred as "false positives", therefore astronomers need follow-up ground based photometry to verify the exoplanet nature of TESS PCs. In this paper, we conduct ground-based transit photometry on two planets candidates declared in TESS, TOI-5278.01 and TOI-4439.01 with an 80cm telescope at Xinglong Observatory, P.R. China. Our data processing pipeline comprises of three parts: image reduction, aperture photometry and EXOFAST fit. For TOI-4439.01, our result is in accordance with TESS data, proving the exoplanet nature, while the EXOFAST fit did not converge for TOI-5278.01 due to low SNR in the light curve.

Key words: Exoplanet – Transit Photometry – TESS – Data Reduction – EXOFAST Fit

1 INTRODUCTION

The Transiting Exoplanet Survey Satellite (Ricker et al. 2015) is an all-sky survey mission led by MIT and NASA in search of exoplanets by means of seeking for dimming events associated with transits in the light curve of nearby stars. TESS was launched into space aboard a SpaceX Falcon 9 rocket on April 18, 2018. 42 days after launch, TESS arrived in its 2:1 lunar-resonance orbit in which it spends most of its time surveying the sky with no obstacles in its view and downlinks data at the perigee. The satellite features four identical CCD cameras each capable of covering an area of 24×24 square degrees on the celestial sphere. Up till 2021, TESS had provided astronomers with high-quality data which not only identified approximately 3,000 new exoplanet candidates but also revolutionized research on multi-planetary systems, supernovae, supermassive black holes, outbursts of comets, stellar flares, etc.

However, among the transits signals detected by TESS, some of them are not caused by a transiting planet, and they are often referred to as false positives. A typical cause of these false signals in observed light curves are stellar eclipsing binary, artifacts from red noise and other instrumental effects, which were discussed by Deeg & Alonso 2018. Therefore, to verify the exoplanet behind a transit signal, astronomers need ground-based seeing-limited photometric follow-up observations for the TESS discoveries, which were led by the TESS Follow-up Observing Program Working Group (Collins 2019). Ground-based observations usually have a larger pixel scale thus better resolution, therefore more reliable in identifying exoplanets.

To identify false positive candidates of transits, astronomers need to take a closer look at the stellar spectra of the host star. The TESS Follow-up Observing Program (TFOP) Sub Group 2 (SG2) obtained reconnaissance spectra to find evidence of false positives (Giacalone et al. 2022), e.g., spectroscopic binary.

High resolution spectroscopy reveals various properties of the properties of host stars and planets, e.g. mass, age, and metallicity, etc. To further extract the features of the confirmed transiting planets, high resolution spectroscopy is used to reduce the uncertainty in the sizes of Kepler stars and planets in the CKS project (Petigura et al. 2017), resulting in a much more powerful study of relation between planets and the properties of the planet and the host star. Therefore, obtaining the stellar spectra of the host star plays a vital role in the exoplanet detection pipeline.

In this paper, we conduct ground-based photometric follow-up observations for two TESS planetary candidates, TOI-4439.01 and TOI-5278.01 in an attempt to verify their exoplanet nature. We will obtain their transit light curves and try to fit it for physical parameters. Our target selection process are discussed in Part 2. Image reduction, aperture photometry and EXOFAST fit are covered in part 3. We present our results in Part 4. Our data were obtained from Xinglong Observatory, P.R. China during May 13-14, 2022. We used AstroImageJ and EXOFAST to process our data.

2 TARGET SELECTION AND OBSERVATIONS

2.1 Target Selection

To ensure that our observations provide effective data, we searched for potential targets considering with the following factors. First, it is a planet candidate (PC) with a transit depth larger than 10ppt and a magnitude brighter than 15. We found 5 potential target candidates according the stated criteria, as shown in Figure 1.

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Target name	RA	Dec	V mag	Transit Depth	Transit Time
TOI-5278.01	19:43:14	66:34:17	17.46	97.35ppt	31min
TOI-3889.01	12:01:02	55:50:47	13.14	21.19ppt	2h10min
TOI-4439.01	18:57:07	48:32:16	14.54	18.78ppt	2h54min
TOI-4427.01	9:00:12	72:08:52	12.08	21.40ppt	2h28min
TOI-3974.01	15:44:57	45:27:40	14.19	18.27ppt	1h41min

Figure 1. potential Targets

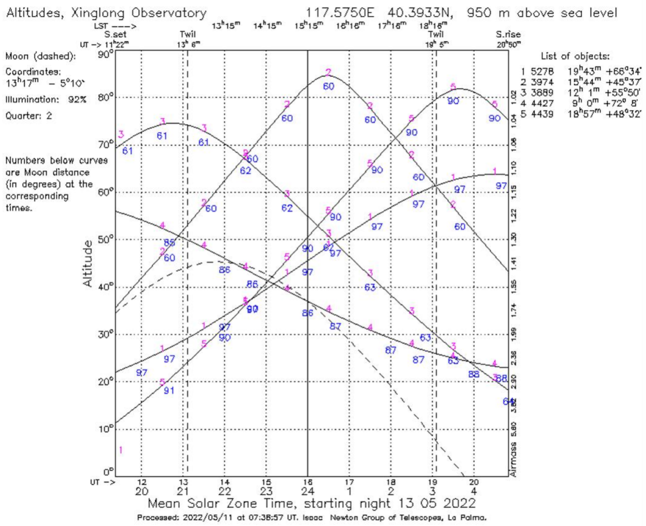

Figure 2. Airmass and Moon Distance of Potential Targets

Target	Date	Transit Time	Band	Frames
TOI5278	May 13	1:10-01:41	V	13 × 240s
TOI5278	May 14	22:04-22:35	V	-
TOI4439	May 14	23:20-02:14	B,R	22 × 400/100s

Table 1. Observation Plan (Actual)

To make sure the targets are observable within the nautical twilight of May 13 or May 14, which is our observation time, we narrowed down our choices to TOI-5278.01 and TOI-4439.01, considering moon distance, airmass (see Figure 2 for details).

TOI-5278.01 is a Jupiter-sized planet orbiting an M-dwarf with a period of 0.4 days, which is rare, and a transit depth of 97ppt. It has few previous observations and transits on both May 13 and May 14, therefore it is a promising target for us. TOI-4399.01 has no previous photometric observation as well as a rare physical nature. It is a warm Jupiter orbiting around a G star, and its transit could be observed in both V and B band. Its transit takes place on May 14 and does not overlap with TOI-5278.01.

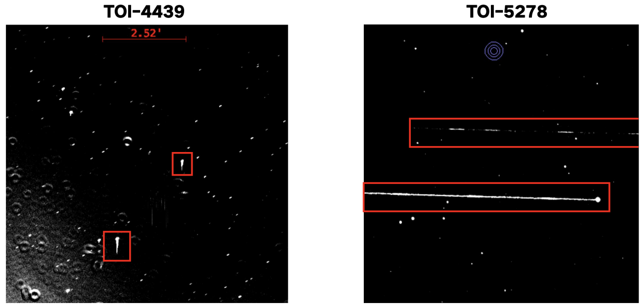

Figure 3. Abandoned Images After Reduction

2.2 Observation Plan

We planned to do our observations on May 13 and 14, 2022 with an 80cm telescope at Xinglong Observatory, Hebei, P.R. China. Both of our selected targets were observable during this period, and their transits did not overlap. We decided to observe both transit of TOI-4439.01, and V and B band for TOI-4439.01.

However, due to communication errors, the actual photometry we did for TOI-4439.01 is in B and R band. And since the Xinglong observatory had a tight schedule, we only observed TOI-5278.01 on May 13. Our actual observation plan are shown in Table 1.

3 DATA REDUCTION AND ANALYSES

3.1 Image Reduction

We took bias frames and flat frames during our observation on both May 13 and May 14. For every set of data, our image reduction process can be divided into the following steps:

1. Create a master bias frame
2. Create a master flat frame
3. Reduce science image with the frames

The reduction process is described in (1) mathematically. Different bands have different reduction frames.

$$reduced = \frac{science - bias}{(flat - bias)_{normalized}}. \tag{1}$$

We discovered several bad images after reduction, shown in Figure 3. The left image is the first in TOI-4439.01 R band data, in which the stars are weirdly shaped as if the telescope has a irregular point spread function. This was caused by the instability of the telescope during exposure. The second image is from the TOI-5278.01 data, in which we found horizontal lines. A possible explanation for this image is a plane and a satellite passed through the field of view of the telescope during exposure. We abandoned both the first and second image in the two bands of TOI-4439.01, because they have an obvious decrease in flux and the stars are conspicuously motion-blurred. To sum up, we kept 12 frames from TOI-5278.01 V band (abandoning the last frame), and 19 frames for TOI-4439.01 B and R band (abandoning the first two frames). Fortunately, we did not lose a point in the middle of the light curve, since those abandoned images were the first or the last in their frames.

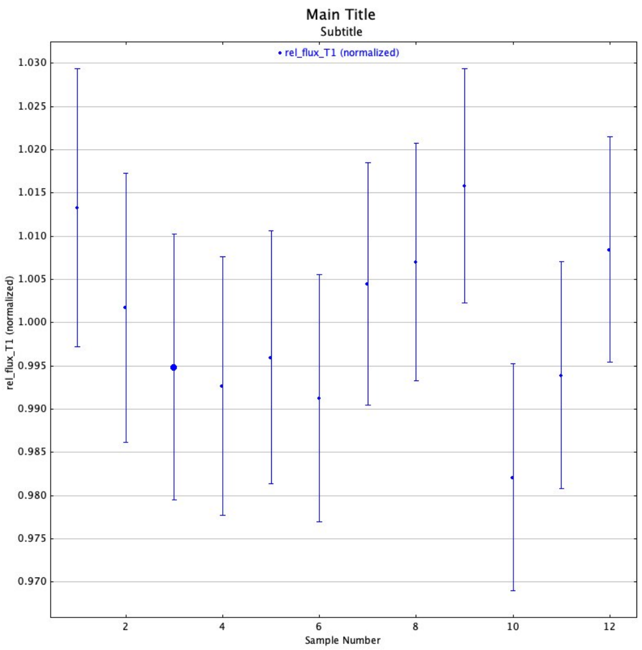

Figure 4. TOI-5278.01 Light Curve

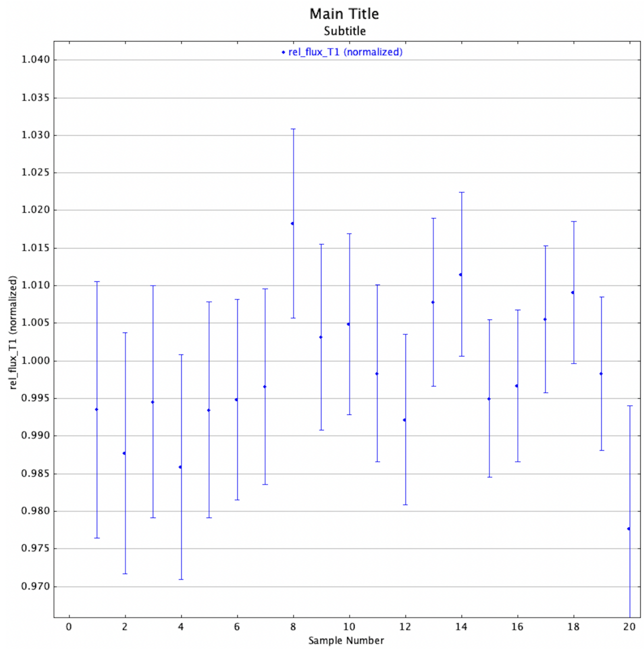

Figure 5. TOI-4439.01 B Band Light Curve

3.2 Aperture Photometry

We conducted aperture photometry with AstroImageJ[1]. The aperture photometry process can be divided in to the following steps:

1. Align all images
2. Identify the target
3. Select comparison stars
4. Calculated light curve of the target
5. Fine tune comparison stars for a better light curve
6. Save the light curve for EXOFAST fit

The obtained light curves are shown in Figure 4, 5 and 6. The TOI-5278.01 curve looks extremely noisy, with huge error bars and no obvious transit. We'll show later that this curve cannot be fitted with EXOFAST.

3.3 EXOFAST Fit

We fitted the obtained light curves with EXOFAST (Eastman et al. 2013) to get the transit parameters. For TOI-5278.01 both Chi-Squared and MCMC method did not converge. It is within our expectation, since the light curve we fed into the fitting models were very noisy, and the number of data points in the curve were not sufficient. For TOI-4439.01, we obtained the following result with Chi-Squared for both V and R band, while MCMC method did not converge. The fitted light curves for TOI-4439.01 are shown in Figure 7,8. The transit appeared on the left of the curve, because our observation did not start exactly when the transit began meanwhile we abandoned several starting frames due to low quality.

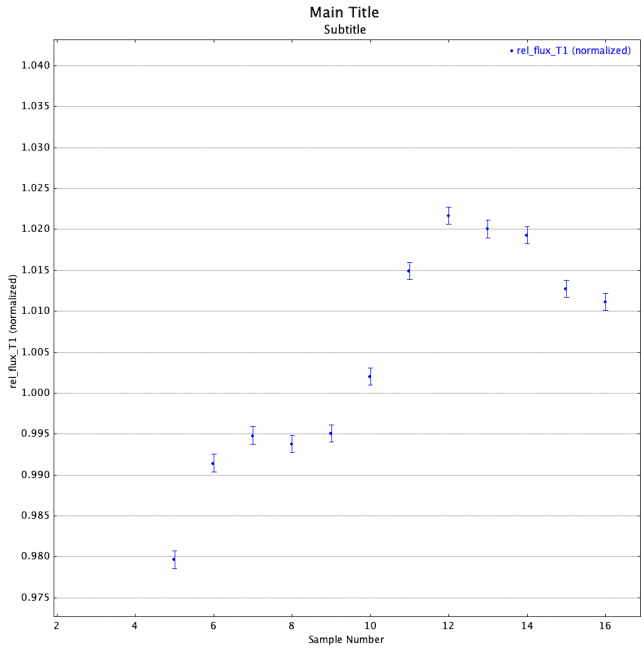

Figure 6. TOI-4439.01 R Band Light Curve

4 RESULTS AND CONCLUSIONS

After conducting image reduction, aperture photometry and EXOFAST fit, we acquired the primary transit parameters, planetary parameters and stellar parameters for TOI-4439.01. We summarized the parameters[2] in Table 2, 3, and 4.

For TOI-4439.01, our fit results of transit time and duration are in

[1] https://www.astro.louisville.edu/software/astroimagej/

[2] For EXOFAST output files, please refer to our Github repository.

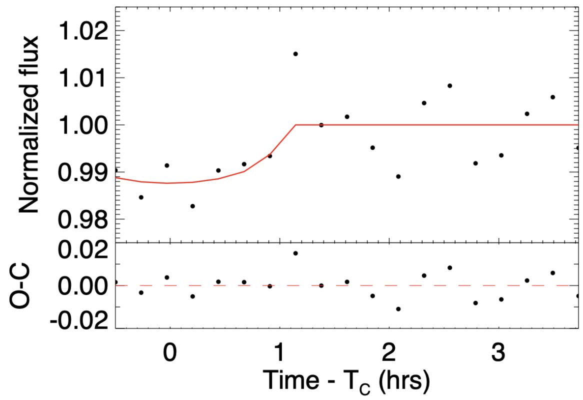

Figure 7. TOI-4439.01 B Band Fit Result

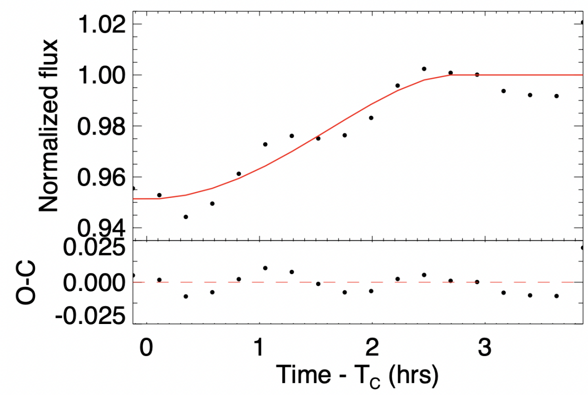

Figure 8. TOI-4439.01 R Band Fit Result

accordance with TESS data, but for other parameters such as transit depth and radius ratio, the R band results differs significantly from TESS and B band results. The B band results are much closer to TESS data, which make sense because TOI-4439.01 are brighter in B band than in R band.

There is also a conspicuous difference between the measured planetary radius of B and R band. The R band data revealed a much larger planetary radius, leading to a much larger planetary ratio, which was probably caused by the large transit depth measured in R band. The B and R band data reached a consensus on all other calculated parameters. It confirms the validity of TESS data and proves TOI-4439.01 is an exoplanet with a transit depth on the scale of ~0.01, orbiting a host star that is approximately 3 times larger than our sun in radius. The planet is similar to Jupiter in size and complete a full orbit every 3.4 days.

As for TOI-5278.01, it is not surprising that we failed to fit its light curve, because it has a much lower SNR (~10) in comparison with TOI-4439.01 (~50). TOI-5278.01 is extremely faint, with a V magnitude of 17.46 and B magnitude of 19.4, which were to blame for the fit failure. Although the transit is deep (97ppt) for TOI-5278.01, we still were not able to obtain a sufficient SNR.

Transit Parameters	B Band	R Band	TESS
Transit Time (BJD)	2459714.164	2459714.153	2459714.201
Transit Depth	0.009242	0.241684	0.018783
Duration (days)	0.114964	0.138146	0.101131
FWHM Duration (days)	0.104853	0.069073	-
Baseline Flux	0.135288	0.149883	-
R_{star}/R_{planet}	0.096133	0.491614	0.13295
Linear Limb-darkening Coefficient	0.707475	0.405560	-
Quadratic Limb-darkening Coefficient	0.114347	0.257636	-
Inclination (degrees)	89.987053	86.129209	-

Table 2. Primary Transit Parameters

Planetary Parameters	B Band	R Band	TESS
Period (days)	3.379236	3.379236	3.379236
Semi-major Axis (AU)	0.043333	0.043318	-
Radius ($R_{jupiter}$)	0.848334	4.317554	-
Equilibrium Temperature (K)	1219.779757	1217.116673	-
Incident Flux	0.502111	0.497740	-

Table 3. Planetary Parameters

Stellar Parameters	B Band	R Band	TESS
Mass (M_{Sun})	0.951320	0.950327	0.97
Radius (R_{Sun})	0.907102	0.902764	0.948617
Luminosity ($_{Sun}$)	0.691010	0.684519	0.7576406
Density (cgs)	1.798855	1.823004	1.602197
Surface Gravity (cgs)	4.501132	4.504842	-
Effective Temperature (K)	5529.600628	5529.805090	-
Metalicity	-0.059736	-0.062148	-

Table 4. Stellar Parameters

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DATA AVAILABILITY

All the data used were taken at Xinglong Observatory, Hebei, P.R. China. The data and code used in this paper can be found on https://github.com/Lukeli0425/Exoplanet-Fit.

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