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Detection of a giant planet in the young system TOI-4562 and follow up

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Abstract. Young planetary systems provide a unique window into the early stages of planetary formation and migration. TOI-4562 b is a Jupiter analog with an extremely eccentric orbit ($e = 0.76$) orbiting a young (< 700 Myr) F7V star. Initial ephemerides indicated strong Transit Timing Variations (TTVs). In this work, we combined TESS archive data with new ground-based observations from the Pico dos Dias Observatory (OPD) to model the system's architecture. Our dynamic analysis reveals the presence of TOI-4562 c, a massive gas giant ($5.77 M_{Jup}$) on a wide ∼ 11-year orbit. Crucially, recent follow-up observations in February 2025 confirmed our model's transit time predictions with high precision, validating the detection. TOI-4562 c currently holds the record for the longest orbital period planet discovered via the TTV method.

Resumo. Sistemas planetários jovens oferecem uma janela única para estudar os estágios iniciais da formação e migração planetária. TOI-4562 b é um análogo a Júpiter com órbita extremamente excêntrica ($e = 0.76$), orbitando uma estrela F7V jovem (< 700 Myr). As efemérides iniciais indicavam fortes Variações de Tempo de Trânsito (TTVs). Neste trabalho, combinamos dados do TESS com observações terrestres do Observatório Pico dos Dias (OPD) para modelar a arquitetura do sistema. A análise dinâmica revelou a presença de TOI-4562 c, um gigante gasoso ($5.77 M_{Jup}$) em uma órbita de ∼ 11 anos. Crucialmente, observações recentes realizadas em fevereiro de 2025 confirmaram as previsões do nosso modelo dinâmico com alta precisão, validando a detecção do companheiro. TOI-4562 c detém o recorde de planeta de maior período orbital descoberto via TTV até o momento.

Keywords. Planets and satellites: detection – Planets and satellites: dynamical evolution – Planets and satellites: individual: TOI-4562

1. Introduction

Young stellar systems are crucial laboratories for astrophysics, marking the era where dynamic processes and rapid changes shape planetary architectures. TOI-4562 b, discovered by Heitzmann et al. (2023) (hereafter HEI23), is a prime example of such a system. It is a temperate Jupiter analogue orbiting a young F7V-type star (< 700 Myr) with an orbital period of $P_{orb} \approx 225$ days. Its high eccentricity ($e = 0.76 \pm 0.02$) suggests a history of violent dynamical evolution or in-situ formation mechanisms that are yet to be fully understood.

The initial ephemeris provided by HEI23 showed Transit Timing Variations (TTV) at the level of 3–15 minutes. While typical for multi-planet systems, the sparsity of the data required further monitoring. TTVs can reveal non-transiting companions, but in young active stars, they can sometimes be mimicked by stellar activity.

In this proceedings, we present the detection of a second giant planet, TOI-4562 c, based on a comprehensive TTV analysis published in Fermiano et al. (2024). Furthermore, we present new observational data obtained in 2025 that confirms the predictions of our dynamic model, solidifying the existence of this wide-orbit companion.

2. Observations

To constrain the system's dynamics, we utilized a combination of high-precision space photometry and targeted ground-based follow-up.

2.1. Ground-based Photometry (OPD/LNA)

We observed a transit of TOI-4562 b on November 09, 2023 (UT), using the 0.6 m Zeiss telescope at the Pico dos Dias Observatory (OPD/LNA), located in Minas Gerais, Brazil. The telescope was equipped with an Andor iXon EMCCD camera, providing a field of view of 6 × 6 arcmin. Observations were conducted in the R filter ($\lambda_c \sim 6450$ Å) with an exposure time of 60 s, achieving a cadence of approximately 1 minute. This observation (Cycle #8) was critical, as it occurred near a predicted TTV extremum. The resulting normalized light curve is shown in Fig. 1.

2.2. Space-based Photometry (TESS)

We retrieved all available data from the Transiting Exoplanet Survey Satellite (TESS). TOI-4562 is in the southern continuous viewing zone, allowing for extensive coverage. Data included:

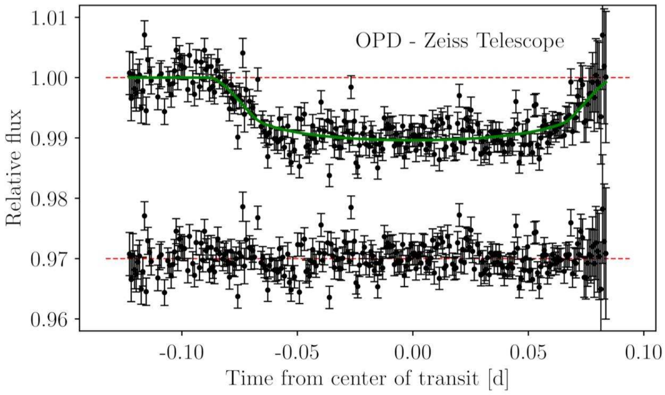

Figure 1. Normalized transit of TOI-4562 b, where the mid-transit resulted in an $O - C$ (observed minus calculated) of $\sim$ 2 hours relative to the HEI23 ephemeris.

- Sectors 1–13 (Year 1): 30-minute cadence.
- Sectors 27–39 (Year 3): 2-minute cadence.
- Sector 63: 20-second cadence.

A total of six transits were identified in the TESS data, including a new event in March 2023 (Cycle #7) not included in the HEI23 discovery paper.

3. Methods and Analysis

3.1. Light Curve and TTV Extraction

We modeled the transit signals using the `batman` package (Kreidberg 2015) coupled with a Markov Chain Monte Carlo (MCMC) implementation via `emcee`. We fitted the planet-to-star radius ratio (k), inclination (i), and scaled semi-major axis (a/R_*), while keeping limb-darkening coefficients fixed to theoretical values. The central transit times (T_c) for each epoch were treated as free parameters to extract the TTV signal.

3.2. N-Body Modeling

The resulting transit times were analyzed using `TTVFast` (Deck et al. 2014), a symplectic N-body integrator designed for exoplanetary systems. We modeled the system as the star plus two massive planets. To break the known degeneracy between planet mass and eccentricity in TTV signals, we used the mass of the inner planet TOI-4562 b derived from radial velocities in HEI23 as a Gaussian prior.

The parameter space for the third body (TOI-4562 c) was explored using MCMC with 50,000 steps and 16 walkers. We searched for solutions that minimized the χ^2 between the observed and calculated transit times.

4. Results

4.1. Updated Ephemeris and System Architecture

The ground-based observation at OPD revealed a massive deviation from the linear ephemeris. The transit occurred approximately 2 hours earlier than predicted by the HEI23 linear model ($O - C \approx -116$ min). This large amplitude signal strongly constrained the TTV model.

Our best-fit N-body solution indicates the presence of a non-transiting outer companion, TOI-4562 c. The derived parameters are listed in Table 1. TOI-4562 c is a super-Jupiter ($5.77 M_{\rm Jup}$) on a wide, 11-year orbit ($a \approx 5.2$ AU). A schematic comparison of the system's architecture with the Solar System is presented in Fig. 2.

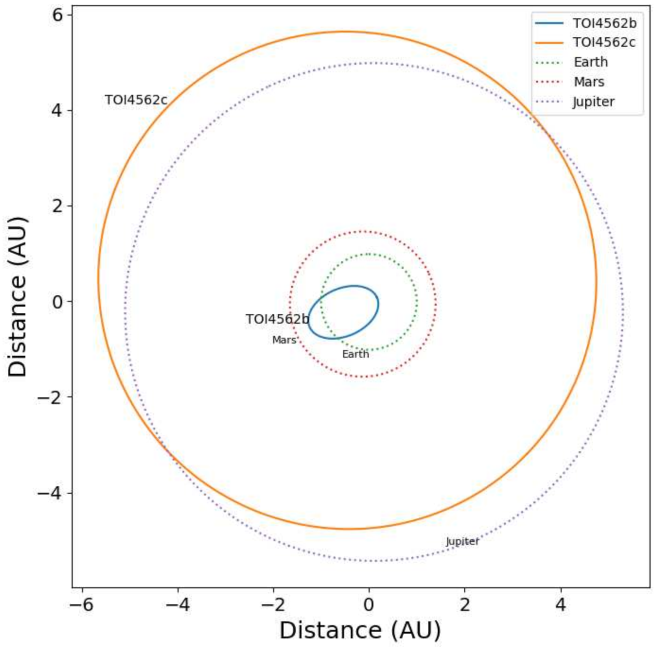

Figure 2. Schematic diagram showing the orbits of TOI-4562 b and TOI-4562 c in comparison with the planets of the solar system.

Table 1. Parameters of the TOI-4562 System (Fermiano et al. 2024)

Parameter	Unit	Value
TOI-4562 b		
Period (P_b)	days	225.10837 ± 0.00015
Eccentricity (e_b)	-	0.76 ± 0.02
T_0 (Linear)	BJD	2459456.8895
TOI-4562 c		
Mass (M_c)	$M_{\rm Jup}$	$5.77^{+0.37}_{-0.56}$
Period (P_c)	days	$3989.80^{+201.23}_{-191.70}$
Semi-major axis (a_c)	AU	5.219 ± 0.002
Eccentricity (e_c)	-	$0.122^{+0.027}_{-0.026}$
Inclination (i_c)	deg	90.0 ± 0.2

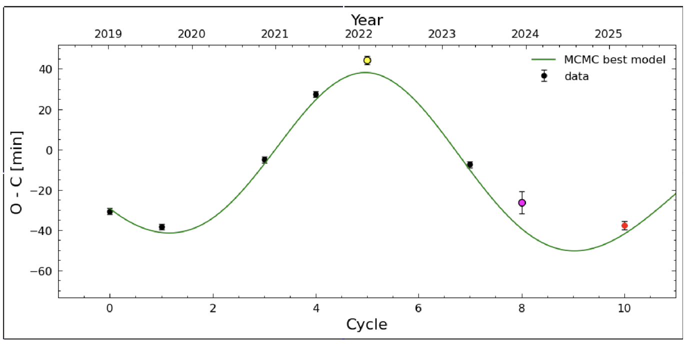

Figure 3. $O-C$ diagram for TOI-4562 b, with the TTV model fit shown as a green curve. The last point (Cycle #10) marks the most recent transit, which deviated by approx. 26 minutes from the model's prediction, in agreement with the TTV model.

4.2. Discussion: Stability and Alternative Scenarios

Given the young age of the star, we considered if the TTV signal could be induced by stellar activity, specifically the Applegate effect. For a solar-type star to produce TTV variations of ∼ 2 hours via the Applegate mechanism, the required energy to modulate the stellar quadrupole moment would be unphysically high, and the magnetic cycle period would need to match the TTV period (∼ 2000 days). As discussed in Fermiano et al. (2024), this scenario is highly unlikely compared to the planetary perturbation hypothesis.

Dynamically, the system is intriguing. The period ratio $P_c/P_b \approx 17.7$ places the planets far from low-order mean-motion resonances. The high eccentricity of the inner planet and the presence of a massive outer companion suggest a history of violent dynamical interactions, possibly pointing to planet-planet scattering events typical of young systems settling into stability.

4.3. Model Validation with 2025 Data

A critical test of any TTV model is its predictive power for future transits. In Fermiano et al. (2024), we published predictions for the upcoming Cycles #10 to #15.

We successfully recovered the transit of Cycle #10 in TESS data obtained in February 2025. The observed mid-transit time was consistent with our N-body model prediction ($T_{pred} \approx$ 2460707.95 BJD), deviating by approximately 26 minutes from the refined linear ephemeris, but falling exactly on the TTV curve predicted by the presence of planet c (see Fig. 3).

Furthermore, a subsequent transit (Cycle #11) was observed recently at the Mt. John University Observatory (New Zealand). Preliminary reduction indicates agreement with the model, further validating the system architecture proposed in Table 1. This successful prediction confirms that the large O-C variations are indeed dynamical in nature and not due to stochastic stellar noise.

5. Conclusions

We have confirmed the nature of the TOI-4562 system as a young, multi-planet system hosting at least two gas giants. By combining archival TESS data with crucial ground-based observations from OPD/LNA, we detected TOI-4562 c, a $5.8 M_{\rm Jup}$ planet on a ∼ 5.2 AU orbit.

This discovery is significant for two main reasons:

1. TOI-4562 c is currently the exoplanet with the longest orbital period detected via the TTV method.
2. The system's youth and high eccentricity provide a snapshot of planetary architecture in the aftermath of formation, offering constraints for migration models.

The continued monitoring and the successful recovery of the 2025 transits demonstrate the robustness of the derived solution.

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References

Deck, K. M., Agol, E., Holman, M. J., & Nesvorný, D. 2014, ApJ, 787, 132
Fermiano, V., et al. 2024, A&A, 690, L7
Heitzmann, A., et al. 2023, AJ, 165, 121
Kreidberg, L. 2015, PASP, 127, 1161