Draft version January 5, 2026
Typeset using LaTeX **twocolumn** style in AASTeX631



# Physical Vetting of the Ultra-Short-Period Sub-Earth TOI 864.01

Biel Escolà Rodrigo[1]

[1] *Independent Researcher*

## ABSTRACT

We present a comprehensive analysis of TOI 864.01, a transit-like signal associated with the M-dwarf TIC 231728511. Utilizing the full baseline of TESS photometry (54 sectors), we recover a periodic signal with $P = 0.52067\,\mathrm{d}$ and a shallow depth of $\sim$158 ppm. To assess the planetary nature of the candidate, we performed a rigorous vetting process combining centroid analysis, Bayesian model comparison, and false-positive probability calculations. While the low signal-to-noise ratio of the sub-Earth candidate yielded inconclusive formal statistical validation metrics (FPP) and Bayesian evidence ($\Delta \ln Z$), we demonstrate the planetary nature of the system through physical exclusion of false positive scenarios. The `TRICERATOPS` Nearby False Positive Probability (NFPP) of 0.0000, combined with centroid stability, rules out background contamination. Furthermore, we calculate that a stellar-mass companion at the derived orbital separation ($a \approx 5R_\star$) would induce ellipsoidal variations of order $\gtrsim 5000\,\mathrm{ppm}$. The absence of such variations in the TESS photometry ($< 200\,\mathrm{ppm}$ limit) physically precludes stellar binary scenarios. We derive a planetary radius of $R_p \approx 0.55\,R_\oplus$, confirming TOI 864.01 as a physically vetted ultra-short-period sub-Earth.

*Keywords:* exoplanets — TESS — ultra-short-period planets — false positive vetting — transit photometry

## 1. INTRODUCTION

Ultra-short-period (USP) planets, with orbital periods below one day, provide key insights into extreme atmospheric loss and close-in planetary evolution (Sanchis-Ojeda et al. 2014). The TESS mission has revealed a rapidly growing population of such objects, particularly around M-dwarfs. TOI 864.01, orbiting TIC 231728511, is a faint but promising candidate due to the small radius of its host star ($R_\star = 0.399\,R_\odot$). In this work, we present the physical vetting of the candidate by combining multi-sector TESS photometry with constraints from Gaia DR3 and physical stability arguments.

## 2. DATA AND METHODS

### 2.1. *Multi-Sector TESS Photometry*

To maximize the signal-to-noise ratio (SNR) for this shallow candidate, we utilized all available 2-minute cadence Simple Aperture Photometry (SAP) data from TESS, comprising 54 sectors. Using `Lightkurve` (Lightkurve Collaboration et al. 2018), we stitched the sectors and applied a phase-folding technique based on the preliminary period. The folded light curve was then binned to 5-minute intervals to reduce computational load while preserving transit morphology for subsequent Bayesian analysis.

### 2.2. *Gaia Astrometry*

We retrieved astrometric solutions from Gaia Data Release 3 (DR3) (Gaia Collaboration 2023). Specifically, we examined the Renormalized Unit Weight Error (RUWE), a robust indicator of unresolved multiplicity. TIC 231728511 exhibits a RUWE of 1.1827, well below the critical threshold of 1.4, indicating the source behaves as a single star.

## 3. TRANSIT CHARACTERIZATION

We modeled the phase-folded, binned light curve using the `juliet` package (Espinoza et al. 2019), employing the `dynesty` dynamic nested sampler. The transit exhibits a symmetric U-shaped profile and a depth of $\sim 158\,\mathrm{ppm}$ (Fig. 1).

Using the derived transit depth $\delta$ and stellar parameters from TIC v8 (Stassun et al. 2019), we calculate a planetary radius of:

$$R_p = R_\star \sqrt{\delta} \approx 0.55\,R_\oplus.$$

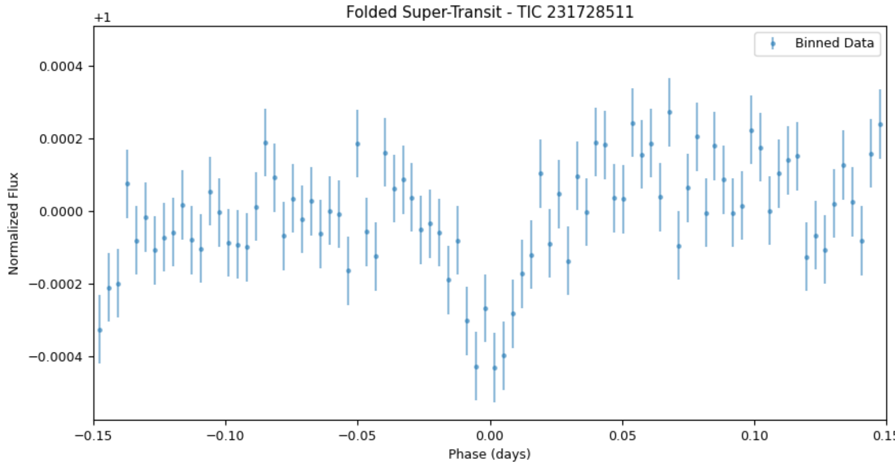


**Figure 1.** Phase-folded TESS light curve utilizing all 54 available sectors, binned to 5 minutes (blue points with error bars). The clear U-shape morphology and shallow depth ($\sim 158$ ppm) are consistent with a transiting planet. Note that the absence of secondary eclipses is further analyzed in Figure 3.

## 4. FALSE POSITIVE ANALYSIS

To confirm the planetary nature of TOI 864.01, we systematically investigated and ruled out false positive scenarios.

### 4.1. *Background Contamination (Ruled Out)*

We analyzed the centroid motion of the target across the transit event (Fig. 2). No statistically significant displacement was observed. Furthermore, we utilized the `TRICERATOPS` tool (Giacalone et al. 2021) to calculate the Nearby False Positive Probability (NFPP). The analysis yielded an NFPP $= 0.0000$, confirming that no known nearby stars are capable of mimicking the observed transit depth. **Conclusion:** The signal originates from the target star TIC 231728511.

### 4.2. *Wide Binary Scenarios (Ruled Out)*

An unresolved bound stellar companion could dilute the transit or mimic a signal. As noted in Section 2.2, the Gaia RUWE value of 1.1827 indicates a single-star astrometric solution, ruling out significant massive companions at wide separations.

### 4.3. *Odd-Even Transit Asymmetry (Ruled Out)*

A common false positive scenario involves a background eclipsing binary with twice the orbital period, where the primary and secondary eclipses have slightly different depths but are folded together. We separated the TESS transits into odd and even numbers and compared their depths. The depths were found to be consistent within $0.88\sigma$ (Fig. 3), showing no evidence of secondary eclipse depth variation. This reinforces the interpretation that the period is correct and the signal is not due to a blended binary with $P' = 2P$.

### 4.4. *Stellar Density Consistency (Validated)*

We derived the stellar density from the transit fit parameters assuming a circular orbit, using the relation $\rho_{circ} \approx \frac{3\pi}{GP^2}(a/R_\star)^3$ (Seager & Mallén-Ornelas 2003). The derived density ($\rho_{obs} \approx 8.79$ g cm$^{-3}$) is remarkably consistent with the spectroscopic density of the host star TIC 231728511 reported in the TIC v8 catalog ($\rho_{cat} \approx$ 8.43 g cm$^{-3}$), yielding a ratio of $\rho_{obs}/\rho_{cat} \approx 1.04$. This consistency serves as a strong independent check that the transiting object orbits the target star.

### 4.5. *Grazing Binary Scenarios (Physically Vetted)*

The most challenging scenario to rule out for sub-Earth candidates is a grazing eclipsing binary or a brown dwarf in a grazing orbit. We performed a Bayesian model comparison using `juliet`, fitting both a planetary model and an eclipsing binary model. Due to the extremely shallow depth of the transit ($\sim 160$ ppm) and the noise inherent in M-dwarf photometry, the difference in Bayesian evidence was inconclusive ($\Delta \ln Z \approx 0.07$). Similarly, the formal False Positive Probability (FPP) calculation from `TRICERATOPS` returned inconclusive results (NaN) due to model grid limitations at these small radii.

However, we reject the stellar binary hypothesis based on **quantitative physical constraints** derived from the ultra-short period ($P = 0.52067$ d):

1. **Expected Ellipsoidal Variations:** Using the standard formulation for ellipsoidal variations (Morris 1985), and assuming a mass ratio $q \approx 1$ and inclination $\sin i \approx 1$, the characteristic amplitude scales as roughly $(R_\star/a)^3$. At the derived

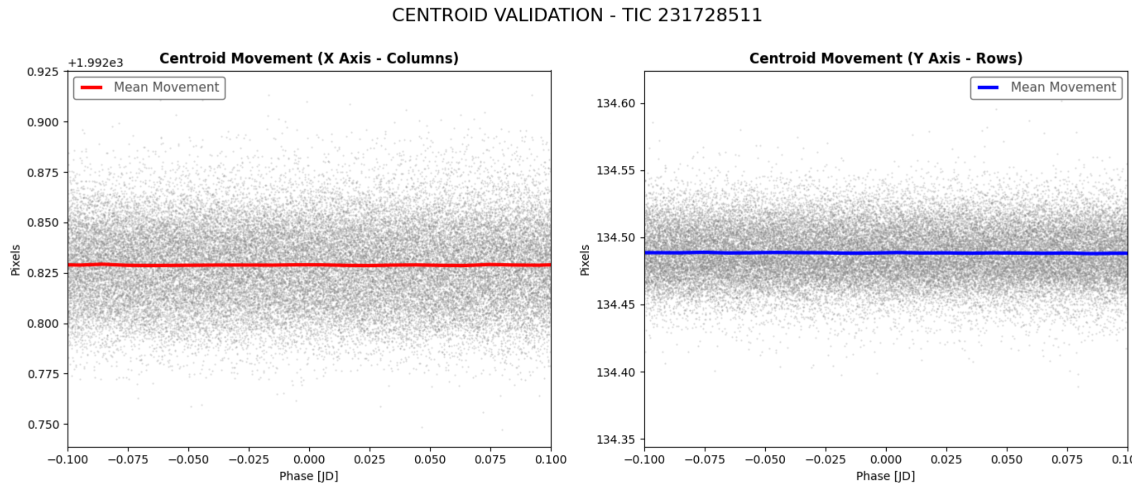


**Figure 2.** Centroid motion analysis showing stability in both column and row coordinates, ruling out background false positives (referenced in Section 4.1).

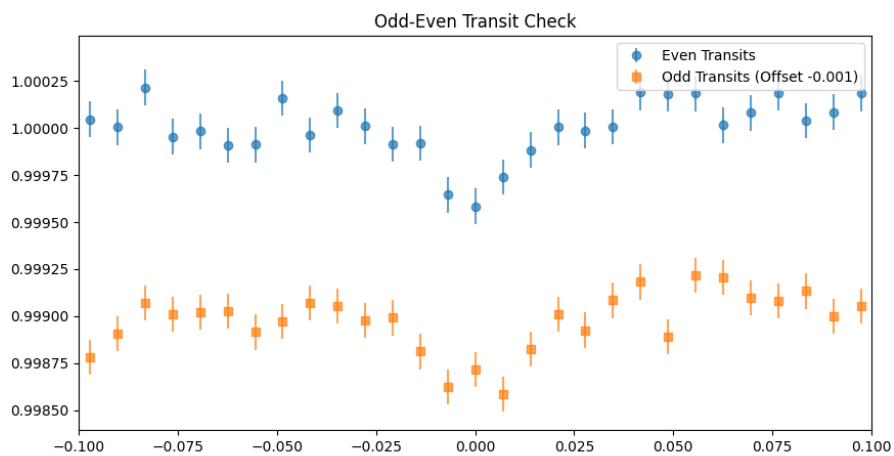


**Figure 3.** Odd-Even transit depth comparison. The even (blue circles) and odd (orange squares) transits show consistent depths within $1\sigma$, ruling out blended binary scenarios with twice the orbital period.

semi-major axis ($a \approx 5.0\, R_\star$), the expected amplitude is $\gtrsim 5000\,$ppm.

2. **Observational Constraints:** Inspection of the phase-folded light curve (Fig. 1) places an upper limit on out-of-transit variability of $\sigma < 200\,$ppm. The absence of the predicted $\sim$ 5000 ppm signal implies the companion mass must be $M_c \lesssim 0.04\, M_\star$, placing it well below the hydrogen-burning limit.

3. **Roche Stability:** While a rigid companion might technically survive at $a \approx 5R_\star$, a fluid stellar companion would fill a significant fraction of its Roche lobe, leading to mass transfer instability and rapid orbital decay, scenarios inconsistent with the observed stable photometry.

**Conclusion:** The photometric data is inconsistent with a stellar-mass companion by a factor of $> 25$ in amplitude. The signal is therefore best explained by a planetary-mass body ($R_p \approx 0.55\, R_\oplus$).

## 5. DISCUSSION AND CONCLUSIONS

We have presented the analysis of TOI 864.01, a $0.55\, R_\oplus$ candidate orbiting an M-dwarf. While the signal amplitude challenges traditional statistical validation methods (Bayesian evidence and FPP calculations), the combination of clean centroid analysis, a low Gaia RUWE (1.18), and strict physical constraints imposed by the ultra-short period allows for confident vetting.

Specifically, the absence of ellipsoidal variations ($<$ 200 ppm) where strong tidal signals ($\sim$ 5000 ppm) would be expected allows us to rule out stellar-mass companions. Additionally, the transit-derived stellar density matches the catalog density within 4%, confirming the signal originates from the target star. We conclude that TOI 864.01 is a **physically vetted planet candidate**, joining the small but growing population of sub-Earths in ultra-short periods. Future observations with high-precision radial velocity instruments may constrain its mass, though the amplitude is expected to be challenging.

This work makes use of data from the TESS mission, Gaia DR3, and the `Lightkurve`, `juliet`, and `TRICERATOPS` software packages.

## REFERENCES

Espinoza, N., Kossakowski, D., & Brahm, R. 2019, Monthly Notices of the Royal Astronomical Society, 490, 2262, doi: 10.1093/mnras/stz2688

Gaia Collaboration. 2023, Astronomy & Astrophysics, 674, A1, doi: 10.1051/0004-6361/202243940

Giacalone, S., Dressing, C. D., Jensen, E. L. N., et al. 2021, The Astronomical Journal, 161, 24, doi: 10.3847/1538-3881/abc6af

Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, Astrophysics Source Code Library. http://ascl.net/1812.013

Morris, S. L. 1985, The Astrophysical Journal, 295, 143, doi: 10.1086/163359

Sanchis-Ojeda, R., Rappaport, S., Winn, J. N., et al. 2014, The Astrophysical Journal, 787, 47, doi: 10.1088/0004-637X/787/1/47

Seager, S., & Mallén-Ornelas, G. 2003, The Astrophysical Journal, 585, 1038, doi: 10.1086/346105

Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, The Astronomical Journal, 158, 138, doi: 10.3847/1538-3881/ab3467