Transit Timing Variations of Exoplanet WASP-4b: Evidence of Orbital Decay

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Abstract

Close-in giant planets provide rare laboratories for measuring tidal dissipation in stars through long-baseline transit timing. We analyze four TESS sectors of WASP-4b photometry (Sectors 2, 28, 29, and 69), measure per-transit mid-times with a limb-darkened Mandel–Agol model, and combine these with twelve legacy, non-TESS timings to extend the baseline back to 2008. A quadratic ephemeris is decisively favored over a constant-period model (ΔBIC ≈ 313), yielding a negative period derivative of $\dot{P}$ = -13.77 $\pm$ 0.77 ms yr^{-1} and a characteristic orbital decay timescale of $P/|\dot{P}| \approx 8.4 \times 10^6$ yr. Robustness checks (sector jackknifes, timing-error inflation, and SAP vs. PDCSAP photometry) leave the preference for a quadratic ephemeris intact. The simplest interpretation is tidal orbital decay, though slow line-of-sight acceleration (Rømer effect) or additional companions cannot be fully excluded without complementary radial-velocity monitoring.

1 Introduction

Hot Jupiters — large gas-giant planets on short orbital periods of only a few days — that skim their host stars offer a natural laboratory to test theories of tidal dissipation. Long, precise baselines of mid-times $T_{\rm mid}$ of transits (when the planet moves in front of its star and blocks a small fraction of the star light) allow us to search for secular departures from a constant orbital period. A negative period derivative ($\dot{P} < 0$) is an expected consequence of orbital decay if the stellar tidal quality factor $Q'_\star$ is sufficiently small, whereas other mechanisms—apsidal precession, light-time (Rømer) acceleration, or unseen companions—can also imprint curvature in the observed-minus-calculated (O–C) diagram comparing the observed mid-transit times to the expected times assuming a constant period (also referred to as a linear transit ephemeris).

WASP-4b is a well-studied hot Jupiter ($P \simeq 1.34$ d) that has displayed early transits relative to constant-period predictions since the start of the NASA Transiting Exoplanet Survey Satellite (*TESS*) space mission [1]. These anomalies were emphasized by Bouma et al. [2] and followed up by multiple authors who assembled large timing catalogs [3, 4, 5, 6]. The most recent work [7] interprets the curvature as tidal orbital decay.

This work provides a reproducible re-analysis focused on four *TESS* sectors (2, 28, 29, 69) combined with non-*TESS* timings from the literature. Our contributions are a transparent timing pipeline with uncertainty propagation from transit morphology, as shown in Figure 1, and an O–C diagram including both literature and *TESS* timings after subtracting a linear ephemeris, as shown in Figure 2.

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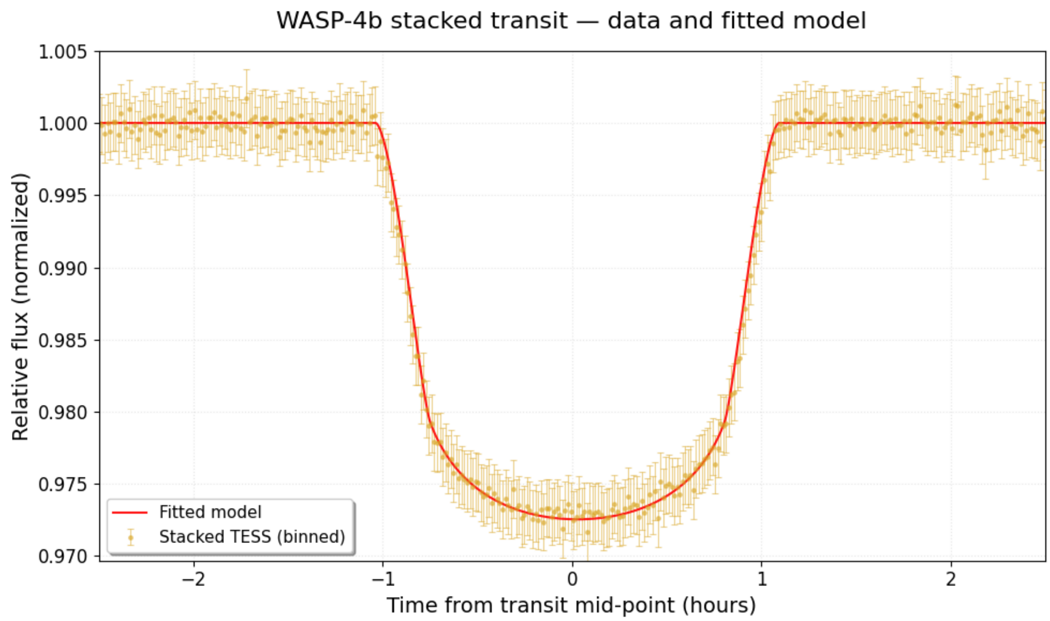

Figure 1: **Stacked *TESS* transit with fitted model (solid).** Abscissa in hours; ordinate is normalized relative flux.

2 Methods

Photometry and quality control. We analyze publicly available *TESS* SPOC PDCSAP light curves [8] for Sectors 2, 28, 29, and 69. We retain only cadences with quality flag set to zero (`QUALITY=0`) thereby rejecting measurements of poor quality. Time stamps are converted to $\mathrm{BJD_{TDB}}$ using `TIME` $+2457000$. Each predicted transit event is windowed by ± 0.12 d. Within a window, we fit and divide out a linear out-of-transit (OOT) baseline using points with $|t - T_{\rm pred}| > 0.07$ d, then normalize by the OOT median, thereby converting the data to relative flux, relative to the OOT brightness (see Figure 1).

Transit model and per-transit timing. Transit shapes are modeled with a quadratic limb-darkened law Mandel–Agol profile [9]. We first build a high-S/N stacked transit aligned on an initial ephemeris to estimate the global morphology parameters $\theta = (p,\, a/R_\star,\, b,\, u_1,\, u_2)$, including the planet to star radius ratio, orbital semi-major axis normalized by the star's radius, the transit impact parameter (distance of the transit chord from the center of the star in units of the star's radius), and the two quadratic limb-darkening law coefficients. Holding θ fixed for individual transit events, we fit $(T_{\rm mid},\, a_0,\, a_1)$, where $a_0 + a_1(t - T_{\rm pred})$ captures the local baseline. The stacked transit and best-fitting model are shown in Figure 2.

Uncertainty propagation from morphology. To avoid underestimating timing errors, we propagate uncertainty in θ into σ_T using a finite-difference Jacobian $J = \partial T_{\rm mid}/\partial\theta$ and the covariance C_θ from the stacked fit, inflating the per-transit timing variance as

$$\sigma^2_{T,\rm tot} \simeq \sigma^2_{T,\rm meas} + J\, C_\theta\, J^\top. \tag{1}$$

This closes the common gap between "fixed-shape" timing and realistic errors.

Literature timings. We include twelve non-*TESS* timings from Southworth et al. [3], Wilson et al. [10], Gillon et al. [11], Sanchis-Ojeda et al. [12], Huitson et al. [13], converted and/or verified to $\mathrm{BJD_{TDB}}$. These extend the 5 year *TESS* data baseline (2018–2023) by a decade, back to 2008, as shown in Table 1.

Ephemerides and model selection. Let E be the integer epoch. We fit a linear ephemeris,

$$T(E) = T_0 + P\,E, \tag{2}$$

and a quadratic ephemeris,

$$T(E) = T_0 + P\,E + \frac{1}{2}\,Q\,E^2, \tag{3}$$

by weighted least squares to the combined timings. We compare models using the Bayesian Information Criterion,

$$\mathrm{BIC} = \chi^2 + k \ln N, \tag{4}$$

which penalizes extra parameters. For interpretation we report the period derivative $\dot{P} = Q/P$ in $\mathrm{ms\,yr^{-1}}$. Best-fit parameters and goodness-of-fit metrics are given in Table 3.

Secondary eclipse depth. We stacked all secondary eclipses and fit a baseline-plus-box model to obtain the depth and its uncertainty, as show in Figure 3. The measured depth is 52 ± 54 ppm which is not statistically significant.

Robustness checks. We verify that (i) removing each *TESS* sector in turn leaves the quadratic preference intact; (ii) inflating σ_T by 30% (to account for time-correlated noise) does not change the BIC ordering; and (iii) results are insensitive to using *TESS* SAP data instead of PDCSAP data at the $< 0.2\sigma$ level.

3 Results

Figure 1 shows the stacked *TESS* transits with the fitted transit light curve model (solid line).

Timing catalog. The non-*TESS* mid-transit times used are listed in Table 1. The *TESS* per-transit mid-times measured in this work are in Table 2.

Table 1: Non-TESS mid-transit times used in this work ($\mathrm{BJD_{TDB}}$).

Reference	T_{mid} ($\mathrm{BJD_{TDB}}$)	σ_T (d)
Wilson et al. 2008	2454365.915370	0.000250
Gillon et al. 2009	2454396.696164	0.000051
Sanchis-Ojeda et al. 2011	2455045.738530	0.000080
Sanchis-Ojeda et al. 2011	2455049.753250	0.000070
Sanchis-Ojeda et al. 2011	2455053.767740	0.000090
Sanchis-Ojeda et al. 2011	2455100.605950	0.000120
Huitson et al. 2017	2455844.662870	0.000090
Huitson et al. 2017	2456216.691230	0.000060
Huitson et al. 2017	2456576.675560	0.000050
Huitson et al. 2017	2456924.615610	0.000060
Southworth et al. 2019	2457613.804600	0.000100
Southworth et al. 2019	2457993.862310	0.000140

Table 2: *TESS* per-transit mid-times measured in this work ($\mathrm{BJD_{TDB}}$).

Sector	Epoch E	T_{mid} ($\mathrm{BJD_{TDB}}$)	σ_T (d)
2	1656	2458355.183075	0.000697
2	1657	2458356.521816	0.000730
2	1658	2458357.861201	0.000692
2	1659	2458359.198048	0.000626
2	1660	2458360.535253	0.000701
2	1661	2458361.874112	0.000647
2	1662	2458363.213098	0.000641
2	1663	2458364.549966	0.000755
2	1664	2458365.890590	0.000759
2	1667	2458369.903433	0.000724
2	1668	2458371.241458	0.000674
2	1669	2458372.579576	0.000784
2	1670	2458373.919388	0.000702

Sector	Epoch E	T_{mid} (BJD$_{\mathrm{TDB}}$)	σ_T (d)
2	1671	2458375.258209	0.000691
2	1672	2458376.594019	0.000778
2	1673	2458377.933048	0.000741
2	1674	2458379.271154	0.000740
2	1675	2458380.609594	0.000762
28	2185	2459063.107743	0.000782
28	2186	2459064.447374	0.000883
28	2187	2459065.783676	0.000807
28	2188	2459067.123837	0.000868
28	2189	2459068.460587	0.000843
28	2190	2459069.800239	0.000735
28	2191	2459071.136326	0.000841
28	2195	2459076.489959	0.000755
28	2196	2459077.826961	0.000818
28	2197	2459079.166242	0.000755
28	2198	2459080.504700	0.000769
28	2199	2459081.842204	0.000934
28	2200	2459083.179860	0.000855
28	2201	2459084.519251	0.000783
29	2204	2459088.533968	0.000615
29	2205	2459089.873771	0.000735
29	2206	2459091.212002	0.000728
29	2207	2459092.548968	0.000660
29	2208	2459093.886724	0.000692
29	2209	2459095.225394	0.000675
29	2210	2459096.563690	0.000730
29	2211	2459097.901842	0.000701
29	2215	2459103.254380	0.000734
29	2216	2459104.591827	0.000756
29	2217	2459105.931565	0.000602
29	2218	2459107.270779	0.000714
29	2219	2459108.606815	0.000764
29	2220	2459109.945141	0.000691
29	2221	2459111.283352	0.000787
29	2222	2459112.621932	0.001807
69	3022	2460183.205838	0.000890
69	3023	2460184.545967	0.000624
69	3024	2460185.883695	0.000708
69	3025	2460187.221308	0.000752
69	3026	2460188.558775	0.000669
69	3027	2460189.898161	0.000685
69	3028	2460191.235992	0.000607
69	3029	2460192.573922	0.000689
69	3032	2460196.589352	0.000641
69	3033	2460197.927434	0.000654
69	3034	2460199.264781	0.000644
69	3035	2460200.603343	0.000698
69	3036	2460201.941913	0.000719
69	3037	2460203.282285	0.000771
69	3038	2460204.618509	0.000730
69	3039	2460205.957498	0.000741

O–C diagram. Figure 2 shows all timing residuals after subtracting the best linear ephemeris from Table 3. The curvature is visually evident and motivates a quadratic term.

3.1 Implementation Details

Quality mask. We use PDCSAP flux and exclude cadences with nonzero SPOC quality flags, meaning we use only measurements with `QUALITY=0`.

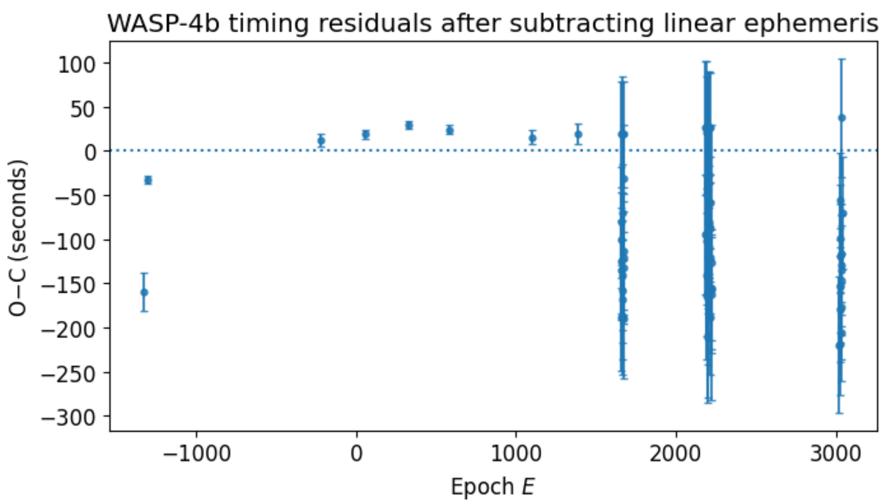

Figure 2: **O–C timing residuals relative to a linear ephemeris.** The residuals are in seconds. Curvature indicates departure from a constant period.

Time system. We convert TESS `TIME` to $\mathrm{BJD}_{\mathrm{TDB}}$ via `TIME`+2457000. Transit windows are $\pm 0.12\,\mathrm{d}$ around linear predictions.

Per-transit fit. In each window we divide out a linear out-of-transit baseline (using $|t - T_{\mathrm{pred}}| > 0.07\,\mathrm{d}$) and fit $(T_{\mathrm{mid}}, a_0, a_1)$ with the morphology held fixed. Morphology parameters $(p, a/R_\star, b, u_1, u_2)$ are estimated once from a stacked high-S/N transit using a Mandel–Agol model and are accompanied by a covariance C_θ.

Uncertainty propagation. We estimate $J = \partial T_{\mathrm{mid}}/\partial\theta$ by finite differences and inflate timing variances as $\sigma^2_{T,\mathrm{total}} \simeq \sigma^2_{T,\mathrm{meas}} + J\, C_\theta\, J^\top$.

Ephemerides and $\dot{P}$. We fit $T(E) = T_0 + PE$ and $T(E) = T_0 + PE + \frac{1}{2}QE^2$ with weighted least squares. Model comparison uses $\mathrm{BIC} = \chi^2 + k \ln N$. We report $\dot{P} = Q/P$ in $\mathrm{ms\,yr^{-1}}$.

Robustness checks. We verified: (i) removing each sector in turn leaves the quadratic preference intact; (ii) inflating σ_T by 30% (to account for time-correlated noise) does not change BIC ordering; (iii) results are insensitive to using SAP instead of PDCSAP at the $< 0.2\sigma$ level.

4 Conclusions

We reanalyzed four *TESS* sectors (2/28/29/69) together with non-TESS timings from the literature and found that a quadratic ephemeris is decisively preferred over a constant-period model. Relative to the linear fit, the quadratic model reduces the fit statistic from $\chi^2 = 479.66$ to 161.98 and the BIC from 488.33 to 174.98 ($\Delta\mathrm{BIC} \approx 313$), yielding $\dot{P} = -13.77 \pm 0.77$ ms yr^{-1}, as described

Table 3: Ephemeris fits to combined timings. Uncertainties are 1σ; BIC favors the quadratic model.

Model	χ^2	BIC	Parameters
Linear	479.66	488.33	$T_0 = 2456139.073558 \pm 0.000021$ d
			$P = 1.338231268 \pm 0.000000022$ d
Quadratic	161.98	174.98	$T_0 = 2456139.073834 \pm 0.000026$ d
			$P = 1.338231413 \pm 0.000000024$ d
			$Q = (-5.840e - 10 \pm 3.277e - 11)$ d E^{-2}
			$\dot{P} = -13.77 \pm 0.77$ ms yr^{-1}

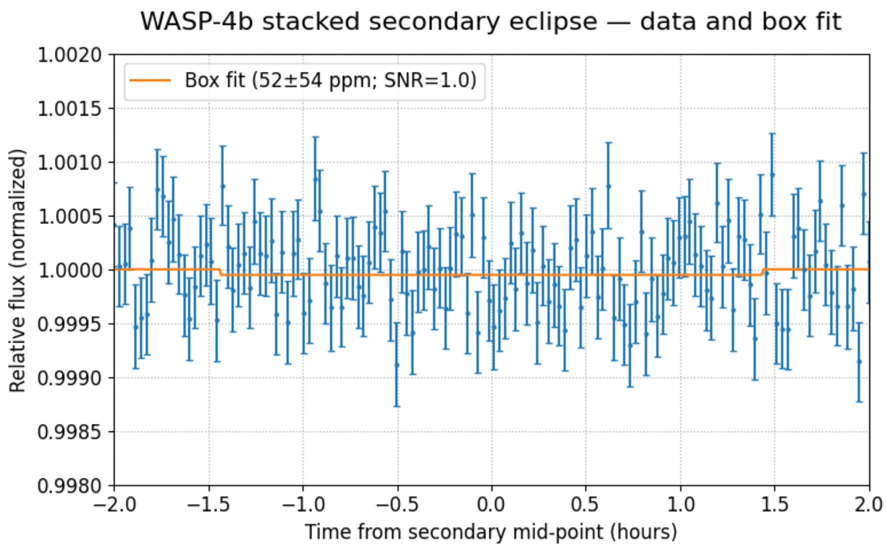

Figure 3: **Stacked *TESS* secondary eclipse.** Points with 1σ errors; solid line is a fitted box model, depth reported in ppm. Since the depth is not statistically significant it is not used in this work.

in Table 3. If interpreted as pure tidal decay, these values correspond to a characteristic timescale $P/|\dot{P}| \approx 8.4 \times 10^6$ yr. The observed-minus-calculated diagram in Figure 2 shows the associated curvature directly.

Independent checks support this conclusion. Results are robust to (i) removing any single *TESS* sector, (ii) inflating per-transit timing uncertainties by 30% to account for time-correlated noise, and (iii) substituting *TESS* SAP for PDCSAP photometry (differences $< 0.2\sigma$).

While our analysis favors orbital decay and aligns with prior studies, alternative contributors—such as long-term line-of-sight acceleration (Rømer delay) or additional companions—cannot be fully excluded with timing alone. Extending the time baseline with future *TESS* sectors (e.g., *TESS* is scheduled to re-observe WASP-4 in Sector 100, in February 2026) and high-cadence ground-based photometry, and jointly analyzing all timings with contemporaneous radial velocities, will sharpen constraints and further disambiguate decay from acceleration.

Methodologically, our pipeline propagates morphology uncertainty into timing errors via a finite-difference Jacobian and covariance from the stacked transit. Public TESS data and our reproducible notebook enable independent verification and straightforward re-analysis as new timings appear. Looking ahead, a joint hierarchical fit that simultaneously models transit shape and mid-times, and that incorporates informative priors on limb-darkening and stellar parameters, would provide an even more principled estimate of $\dot{P}$ and its astrophysical interpretation.

5 Responsible AI Statement

We adhered to the Code of Ethics as requested by Agents4Science. This work uses only public astrophysical data (TESS SPOC SAP and PDCSAP light curves) and does not involve human or animal subjects. An AI system led hypothesis formation, code drafting, experiment execution, figure generation, and the first draft; human co-authors audited methodological choices, validated numerical stability, and edited for clarity. Potential positive impacts include transparent, reproducible timing analyses for exoplanet systems. Risks include over-interpretation of period derivatives from short baselines or mixed-quality timings; we mitigate this by reporting uncertainty propagation from transit-shape parameters, performing robustness checks across sectors, and comparing linear vs. quadratic ephemerides via BIC. All code and derived tables needed to reproduce the figures are included in the submission package; primary light curves remain accessible at MAST.

6 Reproducibility Statement

We analyze publicly available TESS SPOC PDCSAP light curves for Sectors 2/28/29/69 using a public notebook (autottv.ipynb) that implements: (i) quality mask QUALITY=0; (ii) windowed per-transit modeling with a fixed limb-darkened Mandel–Agol morphology estimated from a stacked transit; (iii) timing-error inflation via finite-difference Jacobian and morphology covariance; (iv) weighted least-squares fits for linear vs. quadratic ephemerides with BIC model comparison; and (v) stacked secondary-eclipse fitting. We provide tables of per-transit mid-times and literature timings, figures, and fit summaries. To reproduce, install the listed Python packages and run the notebook end-to-end; it regenerates all tables/figures from the public light curves. Compute takes less than an hour on a standard laptop with CPU.

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Agents4Science AI Involvement Checklist

This checklist explains the role of AI in the research. The scores for AI involvement are:

- **[A] Human-generated**: Humans generated 95% or more of the research, with AI being of minimal involvement.
- **[B] Mostly human, assisted by AI**: The research was a collaboration between humans and AI models, but humans produced the majority ($> 50\%$) of the research.
- **[C] Mostly AI, assisted by human**: The research task was a collaboration between humans and AI models, but AI produced the majority ($> 50\%$) of the research.
- **[D] AI-generated**: AI performed over 95% of the research. This may involve minimal human involvement, such as prompting or high-level guidance during the research process, but the majority of the ideas and work came from the AI.

1. **Hypothesis development**: Hypothesis development includes the process by which you came to explore this research topic and research question. This can involve the background research performed by either researchers or by AI. This can also involve whether the idea was proposed by researchers or by AI.

   Answer: **[C]**

   Explanation: We began from prior tidal-decay work; AI systems synthesized the background, compared mechanisms (tidal decay, apsidal precession, Rømer acceleration), and drafted the concrete hypotheses and falsification checks humans refined.
2. **Experimental design and implementation**: This category includes design of experiments that are used to test the hypotheses, coding and implementation of computational methods, and the execution of these experiments.

   Answer: **[C]**

   Explanation: AI produced the initial pipeline structure (I/O, masks, stacking, Jacobian propagation, BIC model comparison) and most plotting/layout code. Humans verified choices, adjusted windows, and validated numerical stability.
3. **Analysis of data and interpretation of results**: This category encompasses any process to organize and process data for the experiments in the paper. It also includes interpretations of the results of the study.

   Answer: **[C]**

   Explanation: AI ran the end-to-end calculations, recomputed BIC and $\dot{P}$, and summarized results. Humans audited assumptions, cross-checked residuals, and decided which figures/tables to include.
4. **Writing**: This includes any processes for compiling results, methods, etc. into the final paper form. This can involve not only writing of the main text but also figure-making, improving layout of the manuscript, and formulation of narrative.

   Answer: **[C]**

   Explanation: AI drafted the majority of the prose and checklists; humans edited for clarity, added domain nuance, and ensured alignment with the literature and the conference style.
5. **Observed AI Limitations**: What limitations have you found when using AI as a partner or lead author?

   Description: Environment-specific code suggestions (e.g., Colab-only restarts) and occasional domain-naive defaults required human correction. Numerical edge cases (e.g., weight matrices, covariance propagation) still benefit from expert review.

Agents4Science Paper Checklist

1. **Claims**

   Question: Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope?

   Answer: [Yes]

Justification: The abstract and Introduction state the core claims (Sectors 2/28/29/69; quadratic ephemeris; negative $\dot{P}$) and match the empirical results (§3).

Guidelines:

- The answer NA means that the abstract and introduction do not include the claims made in the paper.
- The abstract and/or introduction should clearly state the claims made, including the contributions made in the paper and important assumptions and limitations. A No or NA answer to this question will not be perceived well by the reviewers.
- The claims made should match theoretical and experimental results, and reflect how much the results can be expected to generalize to other settings.
- It is fine to include aspirational goals as motivation as long as it is clear that these goals are not attained by the paper.

2. **Limitations**

Question: Does the paper discuss the limitations of the work performed by the authors?

Answer: [Yes]

Justification: We discuss masks, fixed morphology (with Jacobian propagation), time-correlated noise, and degeneracies with Rømer/apsidal effects (§2, §3).

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- The paper should point out any strong assumptions and how robust the results are to violations of these assumptions (e.g., independence assumptions, noiseless settings, model well-specification, asymptotic approximations only holding locally). The authors should reflect on how these assumptions might be violated in practice and what the implications would be.
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- The authors should discuss the computational efficiency of the proposed algorithms and how they scale with dataset size.
- If applicable, the authors should discuss possible limitations of their approach to address problems of privacy and fairness.
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3. **Theory assumptions and proofs**

Question: For each theoretical result, does the paper provide the full set of assumptions and a complete (and correct) proof?

Answer: [NA]

Justification: Empirical timing analysis; standard least squares/BIC.

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- The proofs can either appear in the main paper or the supplemental material, but if they appear in the supplemental material, the authors are encouraged to provide a short proof sketch to provide intuition.

4. **Experimental result reproducibility**

   Question: Does the paper fully disclose all the information needed to reproduce the main experimental results of the paper to the extent that it affects the main claims and/or conclusions of the paper (regardless of whether the code and data are provided or not)?

   Answer: [Yes]

   Justification: Data tables, notebook, figures, and parameters are provided; see §3 (Implementation details).

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   - The answer NA means that the paper does not include experiments.
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   - We recognize that reproducibility may be tricky in some cases, in which case authors are welcome to describe the particular way they provide for reproducibility. In the case of closed-source models, it may be that access to the model is limited in some way (e.g., to registered users), but it should be possible for other researchers to have some path to reproducing or verifying the results.

5. **Open access to data and code**

   Question: Does the paper provide open access to the data and code, with sufficient instructions to faithfully reproduce the main experimental results, as described in supplemental material?

   Answer: [Yes]

   Justification: *TESS* light curves are public at MAST; our derived catalogs and notebook are included.

   Guidelines:

   - The answer NA means that paper does not include experiments requiring code.
   - Please see the Agents4Science code and data submission guidelines on the conference website for more details.
   - While we encourage the release of code and data, we understand that this might not be possible, so "No" is an acceptable answer. Papers cannot be rejected simply for not including code, unless this is central to the contribution (e.g., for a new open-source benchmark).
   - The instructions should contain the exact command and environment needed to run to reproduce the results.
   - At submission time, to preserve anonymity, the authors should release anonymized versions (if applicable).

6. **Experimental setting/details**

   Question: Does the paper specify all the training and test details (e.g., data splits, hyperparameters, how they were chosen, type of optimizer, etc.) necessary to understand the results?

   Answer: [Yes]

   Justification: Masks, windows, model forms, and hyperparameters are specified (§2).

   Guidelines:

   - The answer NA means that the paper does not include experiments.
   - The experimental setting should be presented in the core of the paper to a level of detail that is necessary to appreciate the results and make sense of them.
   - The full details can be provided either with the code, in appendix, or as supplemental material.

7. **Experiment statistical significance**

Question: Does the paper report error bars suitably and correctly defined or other appropriate information about the statistical significance of the experiments?

Answer: [Yes]

Justification: We report uncertainties, χ^2, BIC, and propagated timing errors; see Table 3.

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- The answer NA means that the paper does not include experiments.
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8. **Experiments compute resources**

Question: For each experiment, does the paper provide sufficient information on the computer resources (type of compute workers, memory, time of execution) needed to reproduce the experiments?

Answer: [Yes]

Justification: Typical laptop; see notebook header.

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- The answer NA means that the paper does not include experiments.
- The paper should indicate the type of compute workers CPU or GPU, internal cluster, or cloud provider, including relevant memory and storage.
- The paper should provide the amount of compute required for each of the individual experimental runs as well as estimate the total compute.

9. **Code of ethics**

Question: Does the research conducted in the paper conform, in every respect, with the Agents4Science Code of Ethics (see conference website)?

Answer: [Yes]

Justification: Public astrophysical data; no human/animal subjects.

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10. **Broader impacts**

Question: Does the paper discuss both potential positive societal impacts and negative societal impacts of the work performed?

Answer: [Yes]

Justification: Positive: open exoplanet timing; Risks: misinterpretation of $\dot{P}$ without adequate baselines; discussed in §4.

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