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Tidal Dissipation and Observable Orbital Decay Windows

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Abstract. Close-in exoplanets offer natural laboratories for star–planet tidal dissipation, but direct observations of orbital decay are few and far between, limiting empirical constraints on stellar tidal quality. Existing investigations are often data-model-intensive and in observationally poor planning, which results in a lack of guidance about quickly identifying closely related systems where decay is detectable on human timescales. This work provides an observationally focused equilibrium-tide baseline to show when orbit decay will be detectable over decade-long baselines. It makes the simplest possible timescale–period map using order-of-magnitude scaling with the modified stellar quality factor ($Q'_\star$), probing typical stellar and planetary parameters, and provide limits for 10-year and 30-year detectability, which matches O–C based on transiting timing baselines. For reference, it position WASP-12 b and Kepler-1658 b based solely on their period and consider one-at-a-time sensitivities from $Q'_\star$, planet mass, and stellar radius. The map demonstrates that only ultra-short periods (T≲2–3 d), strong dissipation (small $Q'_\star$), large planets, and large stellar radii exist in our decade constraint; most known systems exist above these limits, which supports the low rate of strong decay detections. WASP-12 b exists in the limits, while Kepler-1658 b exists on the edge, and is a good candidate for further monitoring. It concludes that ultra-short-period hot Jupiters should be the focus of transit timing with long baselines and high precision; population-level non-detection across long baselines can then yield quantitative limits on stellar $Q'_\star$ and the frequency dependence of stellar tidal dissipation.

Keywords: Orbital Decay, Tidal Quality Factor, Transit Timing

1. Introduction

Close-in exoplanets are usually the best observational targets for star-planet tidal dissipation interactions. Though only a few cases are reported with direct measurements of orbital decay, they also contribute to the sensitive channel, which reveals the stellar tidal dissipation features [1].

This study establishes an observing-field focus for equilibrium tidal effect through the modified stellar quality factor $Q'_\star$. Without heavy modeling, it maps the timescale-period space ($t_a - T$) via the scaling $t_a \propto Q'_\star \frac{M_\star}{M_p} \left(\frac{a}{R_\star}\right)^5 / n$ and sweep typical parameters. It includes 10 and 30 year reference lines that mark declines at decade scales and continue to place public catalog systems' short period systems for orientation [2].

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These results showed that only very short periods (e.g., T $\lesssim$ [2–3] days), combined with larger M_p and smaller $Q'_\star$, fall into decade-scale windows; most systems lie above—consistent with the few literature cases where decay has been reported (e.g., WASP-12 b) [3, 4]. On the other hand, there exists the uncertainty in the form factor of $Q'_\star$ and stellar rotation, but the baseline type still emphasized the short period of hot Jupiters and created a practical list of targets that can be searched for decay in future transit timing monitoring.

2. Method

2.1. Equilibrium tide model and order of magnitude relationship

Allowing for some deviation from the classical equilibrium tide to account for the diminishing effect of tidal bulge on the star exerted torque on the spin and orbit angular momentum, we adopted the RDP tide as an observation-oriented baseline [1]. Using the modified quality factor $Q'_\star \equiv \frac{3Q_\star}{2k_{2\star}}$, the stellar-tide evolution for circular, aligned systems with $\Omega_\star \ll n$ is [5]

$$\frac{da}{dt} = -\frac{9}{2} \times \frac{k_{2\star}}{Q_\star} \times \frac{M_p}{M_\star} \times \left(\frac{R_\star}{a}\right)^5 \times a\left(n - \Omega_\star\right) \tag{1}$$

which implies and order-of-magnitude decay timescale,

$$t_a \approx \frac{2}{9} Q'_\star \frac{M_\star}{M_p} \left(\frac{a}{R_\star}\right)^5 a\,(n - \Omega_\star), \quad \left(n = \frac{2\pi}{T}\right) \tag{2}$$

The scaling highlights the extreme sensitivity to $\left(\frac{a}{R_\star}\right)^5$ [1]; empirical work further suggests $Q'_\star$ spanning $10^5 - 10^7$ across forcing frequencies [6].

As can be seen in Fig. 1.

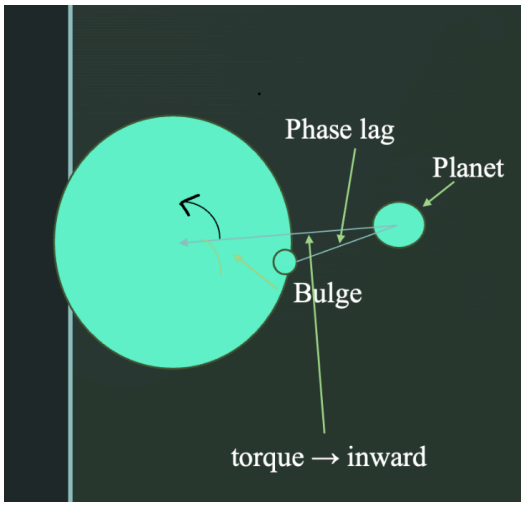


Figure 1. The graph shows how a lagging stellar tidal bulge exchanges angular momentum with the orbit, producing orbital decay when the star rotates more slowly than the orbit. This conceptual sketch motivates the proseonly scaling and the decadescale detectability windows used below (photo/picture credit: original)

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2.2. Data and processing

We build the $t_a - T$ map from a small parameter grid—$Q'_\star \in \{10^5, 10^6, 10^7\}$, $M_p \in \{0.3, 1\} M_J$, $R_\star \in \{0.8, 1, 1.5\} R_\odot$, with $M_\star = 1 M_\odot$ by default. Period is converted to a via

$$a\,[AU] \approx \left(\frac{M_\star}{M_\odot}\right)^{\frac{1}{3}} \left(\frac{T}{1\,\mathrm{yr}}\right)^{\frac{2}{3}} \tag{3}$$

For orientation only, we place the period locations of WASP-12 b (reported decay) and Kepler-1658 b (under verification) on the plot—no additional fitting [3-5]. We note that O–C transit timing is the usual method used for probing; this can only be defined at the decade or 30-year level of visibility windows [6]. Non-tidal TTV sources need to be considered [7].

2.3. Visualization

As can be seen in Fig. 2:

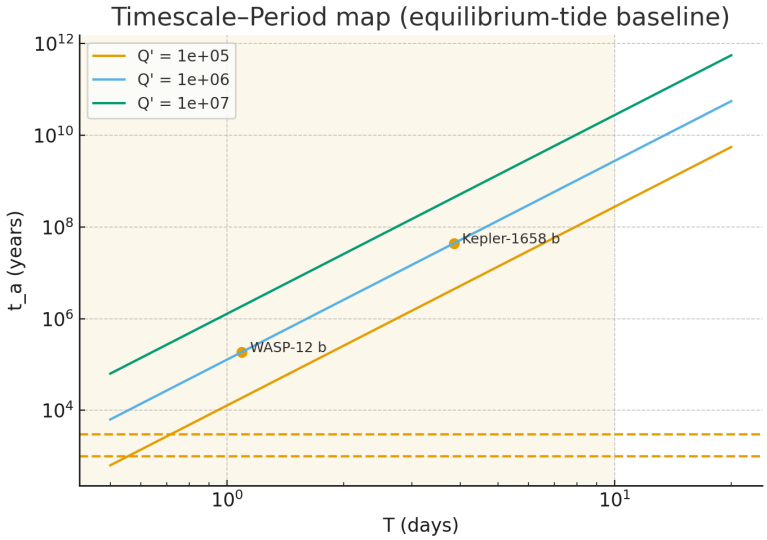


Figure 2. Period and timescale graph. The horizontal lines depict 10- and 30-year references, while the region indicated by the shaded zone is the hot Jupiter zone (T ≤ 10 d). For WASP-12 b and Kepler-1658 b, G from the curves and f from the period are overlaid (period-only on the y-axis) (photo/picture credit: original)

The families of curves include the appropriate values of stellar tidal quality factors ($Q_\star$). The horizontal lines indicate the ten-year and 30-year detectability thresholds, respectively. The band area is specific to hot Jupiters' periods, which are roughly ten days or shorter. The points also refer to WASP-12b and Kepler-1658b, where the lines for periods-only and the fit line overlap.

3. Results

For a fixed $Q'_\star$, t_a rises steeply; therefore, substantial decades/30-yr chances exist only at very short periods (as depicted suggestively), and generally the anti-dissipation lines are close to or above the reference lines unless there is strong dissipation, or baselines are very long.

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The $\left(\frac{a}{R_\star}\right)^5$ term dominates; $Q'_\star$ vertically shifts families by orders of magnitude; larger M_p lowers t_a, and larger $R_\star$ also lowers it via $\frac{a}{R_\star}$. WASP-12 b lies within/near the short-T, strong-dissipation window, consistent with its negative-curvature O–C and millisecond-per-year $\dot{T}$; Kepler-1658 b is at the edge with a possible prime candidate status for future monitoring [3-5].

There are no detections of new clear-cut decays beyond WASP-12 b from the long-term survey, which cautions that decays remain rare and timescales are long [8].

As can be seen in Fig. 3:

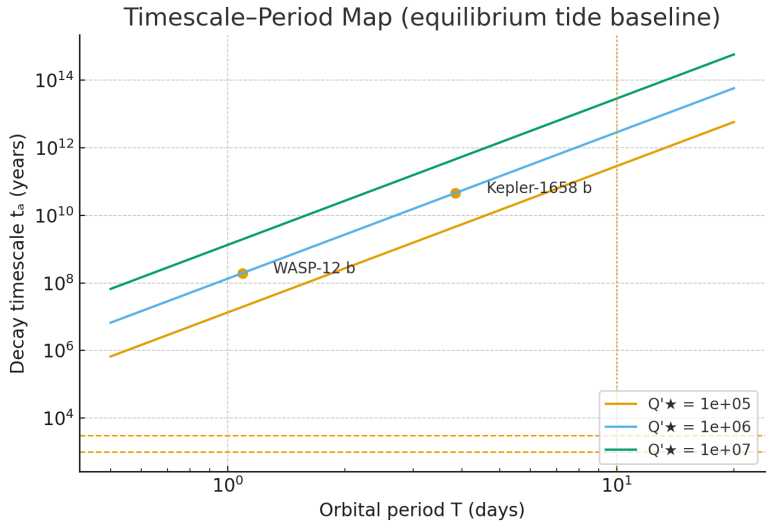


Figure 3. The most important factor affected in the case of other inputs being fixed is the value of (a factor in the timescale of orbital decay); the increase of planet mass and stellar radius also lessens it. The axes scale in a logarithmic scale form (photo/picture credit: original)

4. Discussion

The true $Q'_\star$ likely spans $10^5 - 10^7$, vertically shifting curves and altering window membership; the equilibrium-tide baseline doesn't consider dynamical tides that can increase or reduce dissipation in some stars [1,9]. Systematics or nontidal dynamics can also have an impact on O–C curves. (exomoon/resonance TTV) [7].

Replace $\frac{1}{n}$ by $\frac{1}{|n-\Omega_\star|}$ when spin is significant; tides coupled with magnetic braking shape long-term spin evolution and may flip the torque sign in some regimes [1,10].

Because of transit geometry $P_{transit} \sim \frac{R_\star}{a}$ and deeper dips $\delta \sim \left(\frac{R_p}{R_\star}\right)^2$, short period giants are more likely to be noticed, which explains why hot Jupiters dominate plausible decay candidates [6].

WASP-12 b is within our window of short period and strong-dissipation [3, 4]. Kepler-1658 b sits at the edge [5]. It recommends focusing on very short-T, massive targets, extending baselines and enforcing consistent timing, while sing population-level non-detections to set limits on $Q'_\star$[8, 9].

5. Conclusion

The paper made a baseline focused on observation on purpose; this baseline is for judging when we can detect the tidal orbital decay of close-in exoplanets. We used the equilibrium - tide scaling based

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on the modified stellar quality factor $Q'_{\star}$. It plotted the decay timescale against the orbital period, tested some typical system parameters, and added decade-long timing limits for realistic O–C monitoring campaigns. The created timescale-period map shows the main result clearly. Only short periods (less than about 2-3 days), along with stronger energy loss (smaller $Q'_{\star}$), bigger planets, and larger host-star radii, fit into decade-long time windows. This explains why it's rare to claim robust decay and why systems like WASP-12 b stand out. Borderline cases like Kepler - 1658 b are still useful for continued timing. The framework is made simple on purpose. It quickly focuses on ultra-short-period hot Jupiters for long-baseline, high-consistency transit timing. Also, it lets non - detections at the population level turn into quantitative limits on $Q'_{\star}$ and how it depends on frequency. In future work, key uncertainties like true $Q'_{\star}$ dispersion, dynamical tides, stellar spin, magnetic braking, and nontidal TTV contaminants can be added to this baseline. In practice, the way forward is simple: make the timing baselines the same, target the shortest-period, highest-mass objects around bigger stars, and use both detections and non-detections to improve the understanding of stellar tidal dissipation physics.

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