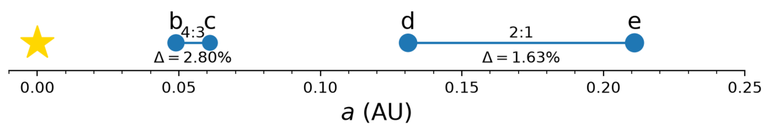
RATTLED BUT NOT BROKEN; The Partially Broken Resonant Chain *TOI-1246* and Its Non-Transiting Companions

Evan Carrasco [1] Fei Dai [1]

[1]University of Hawai'i at Manoa, Institute for Astronomy

Feeling the Unseen: Transit Timing Variations

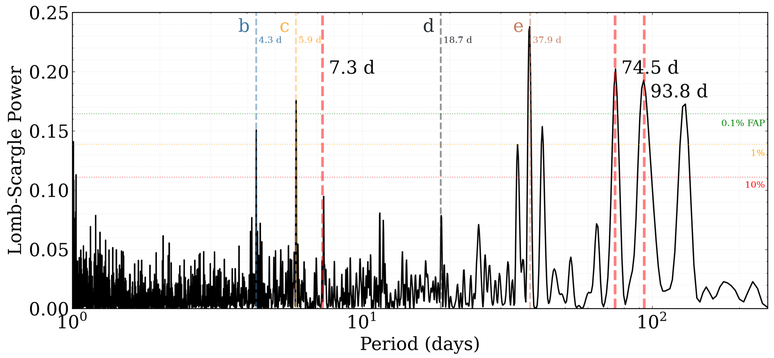
The *Kepler* Mission demonstrated that the majority of nearby planetary systems contain multiple Neptune sized planets within one AU of their host star. The planets of these 'compact-multi' systems are so close together that they induce strong gravitational pulls on one another. These perturbations manifests as periodic variations in a transiting planet's period. **Transit Timing Variations (TTVs) encode the masses and orbital architecture of the perturbed planets, even planets that are not immediately detected from transit observations alone.**



One such compact-multi system that displays strong TTVs is *TOI-1246*[?]. This is a 6.2 Gyr system of 4 transiting planets. This system is interesting for two reasons:

1) TOI-1246 only displays strong TTVs in the outer two planets d and e

2) Additional Radial Velocity (RV) data support one or more non-transiting planets



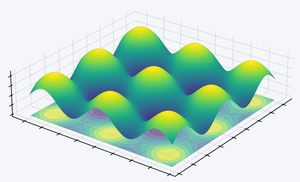
Transit timing data alone is insignificant to detect these non-transiting planets, so we turn to a joint analysis of TTV and RV data to characterize the system.

Mean Motion Resonance

When the perturbations of adjacent planets add constructively the system may become locked into a dynamical state called Mean Motion Resonance (MMR) [2]. Understanding if TOI-1246 is in MMR is crucial to mapping its dynamical history.

JAX and NUTS

To fit TTV and RV data we need to know the complete orbit of the system. This difficult to guess a-priori. Here we use Bayesian inference techniques to back out the planetary parameters from the posterior. **However, with each additional planet we quickly become burdened by the 'curse of dimensionality'.**



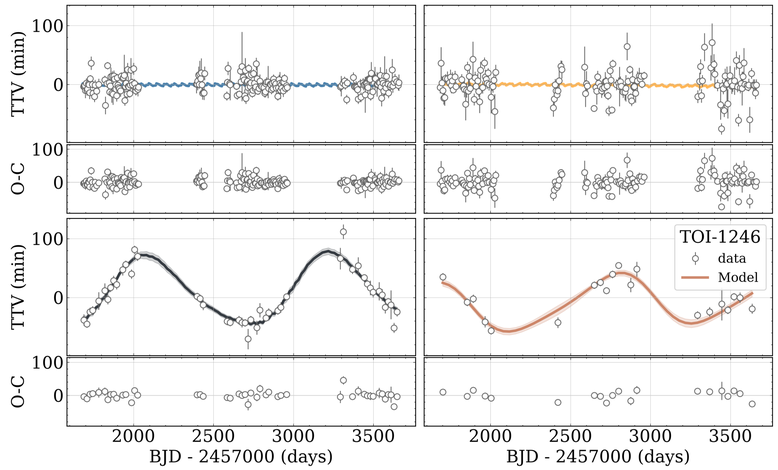
To effectively navigate the parameter likelihood space we employ a Hamiltonian Monte Carlo (HMC) No-U Turn Sampler (NUTS) [3] and `JAX` automatic differentiation [4] to compute model gradients. This allows us to avoid local minimum traps and explore the true best solution quickly.

Guiding Question

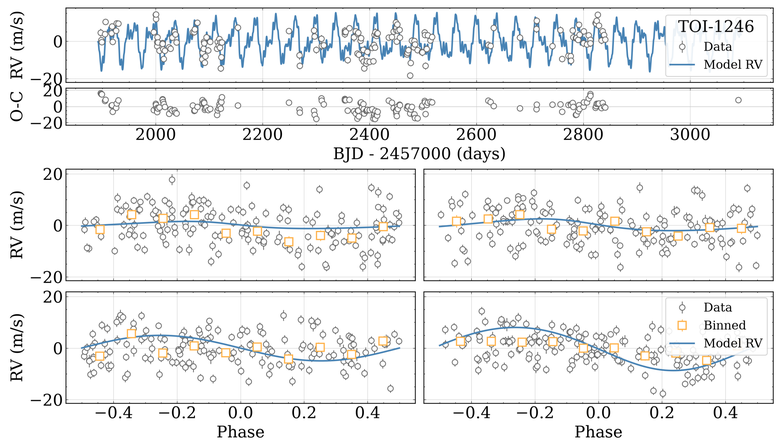
What are the joint TTV + RV fit masses and radii of the planets of TOI-1246? Do one or multiple non-transiting planets better explain the data? Are any planets still in MMR after 6.2Gyr?

Leveraging TTV and RV Data Combined

For this work we use TESS Photometry for transit time measurements and Keck HIRES Spectroscopy for radial velocity. We use Jnkepler [7] to integrate planetary orbits, sampling the parameterized orbital parameters time of inferior conjunction, period, $e\cos\varpi$, $e\sin\varpi$, planet mass, star mass, and γ. We deploy a suite of models exploring the eight permutations of transiting and non-transiting planets. The Bays Information Criterion (BIC) is use to evaluate the goodness of fit weighted by the number of parameters.



We find the that a four planet system with only transiting planets produces the smallest BIC. This supports that the observed additional periodic signals in the Lomb Scargle diagram are either aliasing artifacts or harmonics of transiting planet signals.

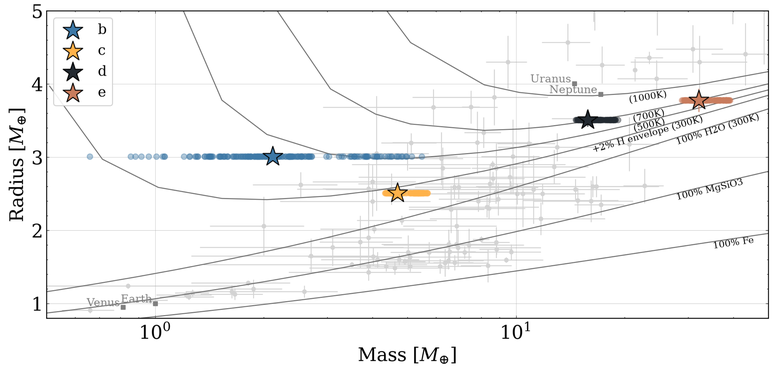


Model Comparison

Non-Transit	None	7d	74d	94d	74,94d	7,74d	7,94d	7,74,94d
BIC	Nan	Nan	Nan	Nan	Nan	Nan	Nan	Nan

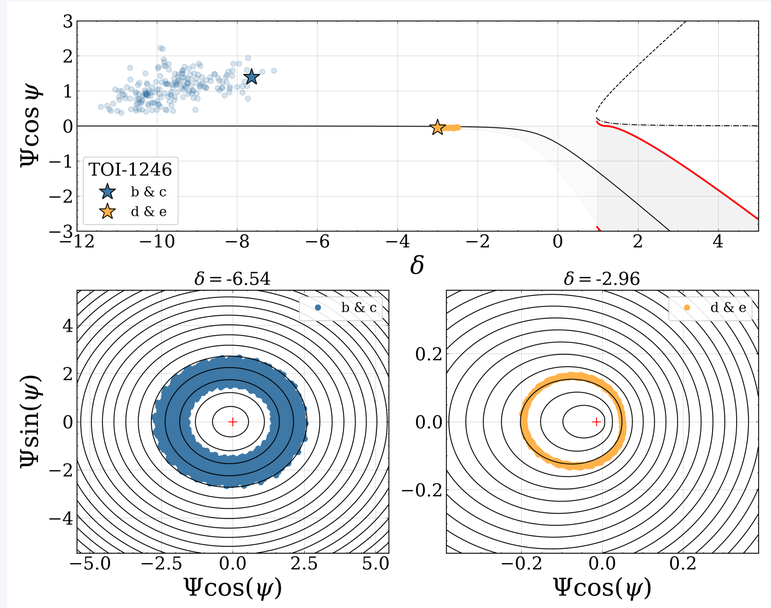
Table 1. BIC for all model permutations

Adopting best fit masses, all transiting planet radii support the retention of an Hydrogen dominated atmosphere.



Proximity to Resonance

The resonant angle of planets b/c and d/e exhibit circulation characteristic of being wide of MMR. We parameterize the proximity to resonance with δ [7]. The period ratio gap of planets c and d is too large to support resonant interactions.



The dynamical state is supportive of TOI-1246 initially forming in a four planet resonant chain with subsequent dynamical upheaval leading to the disruption of resonance between planets b and c. This upheaval leaves the surviving pairs shaken from resonance but not entirely disrupted.

References: *[1] Emma V. Turtelboom, Lauren M. Weiss, Courtney D. Dressing, and et. al. The TESS-Keck Survey. XI. Mass Measurements for Four Transiting Sub-Neptunes Orbiting K Dwarf TOI-1246. , 163(6):293, June 2022* [2] Carl D. Murray and Stanley F. Dermott. Solar System Dynamics. 1999 [3] Eli Bingham, Jonathan P. Chen, Martin Jankowiak, Fritz Obermeyer, and et. al. Pyro: Deep universal probabilistic programming. J. Mach. Learn. Res., 20:28:1–28:6, 2019. [4] James Bradbury, Roy Frostig, Peter Hawkins, and et al. JAX: composable transformations of Python+NumPy programs. 2018. [5] Kento Masuda. jnkepler: Differentiable n-body model for multi-planet systems. ascl:2505.006, 2025. [6] David Nesvorný and David Vokrouhlický. Dynamics and Transit Variations of Resonant Exoplanets. , 823(2):72, June 2016.

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