The Missing Link: Explaining the Origin of V1298 Tau's Broken Resonance Chain

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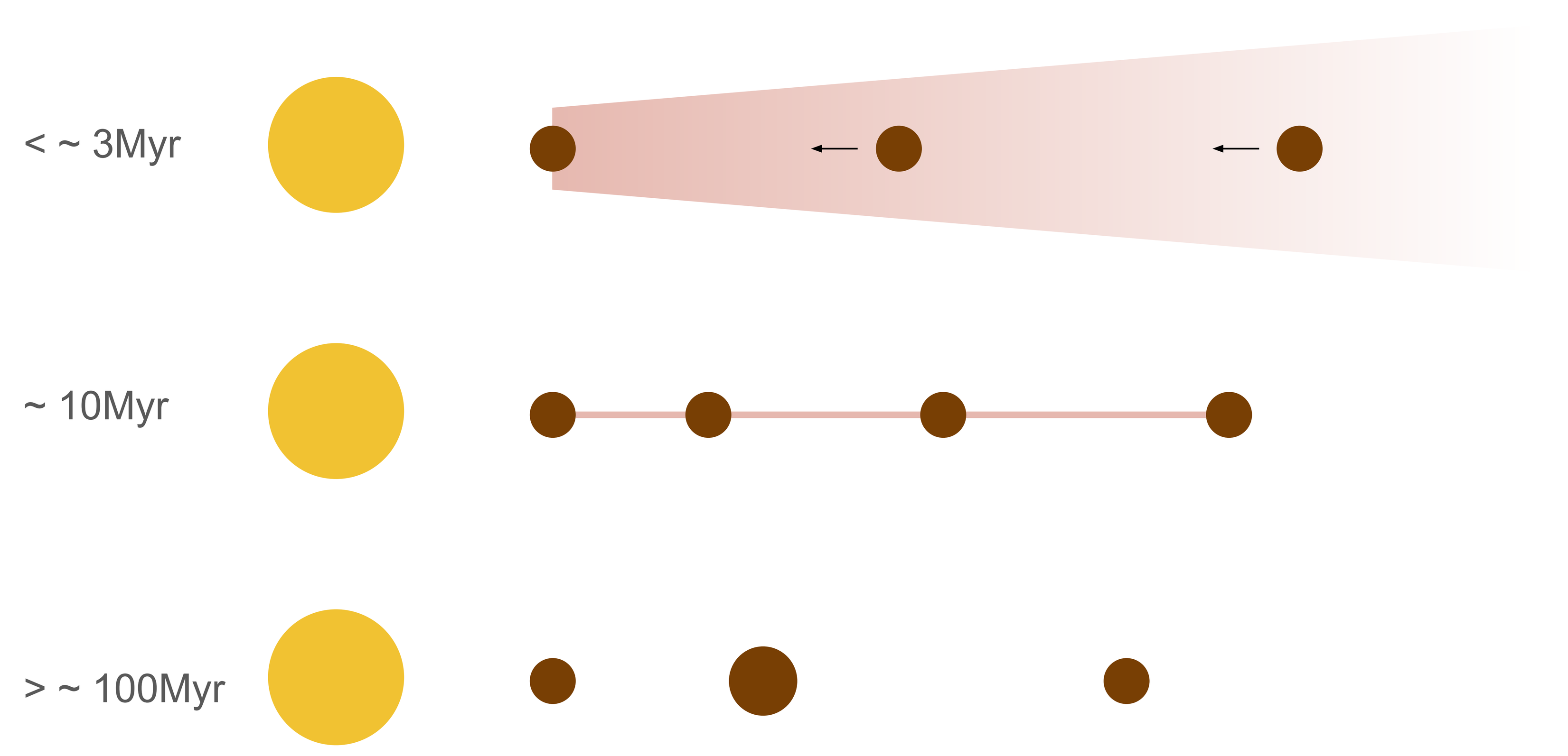
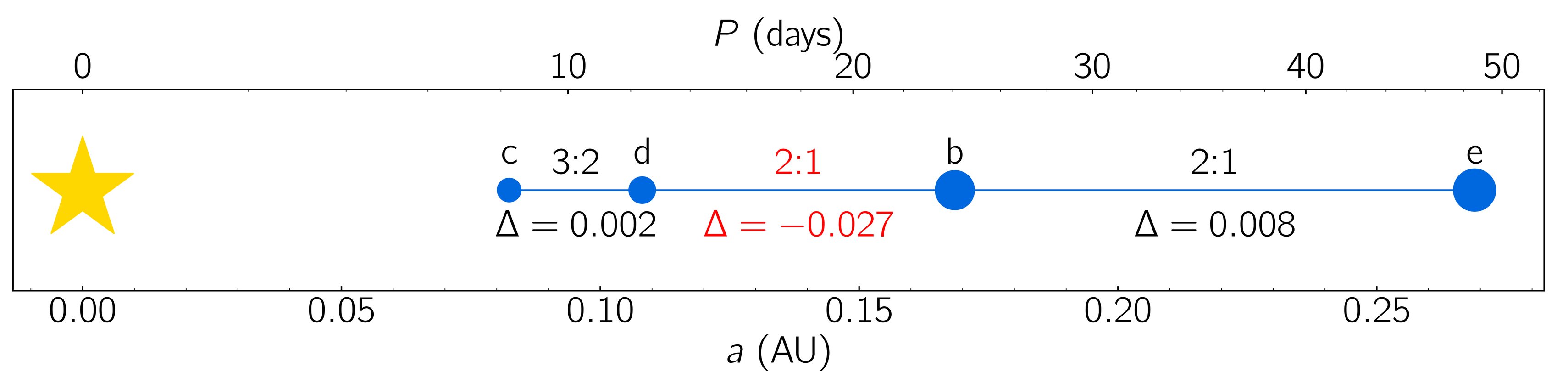
The "Breaking-the-Chains" Model



Many exoplanet systems feature several super-Earths and/or sub-Neptunes in orbits close to their host star (Kepler-like systems), some of which exhibit resonance chains (several consecutive planets with simple whole-number period ratios). These structures are the expected outcome of planetary formation in the context of disk-driven migration [1]. Dai et al. [2] found that the prevalence of these chains strongly depends on age, suggesting that these chains are disrupted on a timescale of ~ 100Myr. **The mechanism responsible for breaking these resonance chains remains uncertain.**

V1298 Tau: A Young, Broken Resonance Chain



V1298 Tau is a young (~ 20Myr old), sun-like star ($\sim 1.1\mathrm{M}_\odot$) hosting a Kepler-like system of 4 planets in resonance [3, 4]. The architecture of the system is shown above. Livingston et al. [5] used TTV measurements to obtain masses of planets in the system, allowing it to be further studied using N-body integrators. **Despite being in a young system, V1298 Tau's resonance chain shows early signs of disruption, providing an excellent opportunity to study the causes of resonance breaking.**

Evidence V1298 Tau b is in a Cassini State

Commensurability between a planet's spin-precession period and its orbit's nodal-precession period can cause capture into a **Cassini state**. In this state, discrepancies between these two periods are compensated for by altering the planet's obliquity (axial tilt). **Through this process, it is possible to excite large obliquities** [6, 7].

Such large obliquities can result in a planet experiencing a large amount of tidal dissipation, which produces an excess of internal heat at the expense of its orbit, which gradually migrates inward. V1298 Tau b displays signs of both of these processes:

1. It's negative fractional deviation with planet d suggests that it initially formed in resonance, but this resonance has since broken and it migrated inward.
2. Atmospheric retrievals using JWST NIRSpec have found that the CH_4 abundance is significantly lower than expected [8]. Equilibrium chemistry models favor a high internal temperature, suggesting internal heating.

We hypothesize that, during the disk phase, V1298 Tau b captured into a Cassini state and was excited to a large obliquity (possibly as high as $\sim 80°$). Afterwards, obliquity tides resulted in the planet migrating inward, breaking the resonance with planet d.

Modeling V1298 Tau's Formation History

To better understand the process, we performed a 2-stage N-body integration using the codes `REBOUND` [9] and `REBOUNDx` [10]. The symplectic integrator `WHFast` [11] with a timestep set to $1/20$th of the innermost planet's orbit (~ 10h) was used for both stages.

In the first stage, we placed each planet 5% wide of the target resonance and simulated the system for 200kyr with convergent migration to form a resonance chain, modeling how the system formed within a protoplanetary disk.

In the second stage, we gradually replaced the disk migration with tidal migration according to the theoretical framework of Hut [12] and Leconte et al. [13] over the course of 10kyr, and proceeded to simulate the system for an additional ~ 10Myr, to model the post-disk evolution of the system.

A sample of the results of these ongoing simulations is shown to the right. We plot both the semi-major axes of the four planets' orbits and their observed fractional deviation, which measures how far a pair of planets are from resonance (see the equation below), as a function of time. We also plot the present observed values for these quantities.

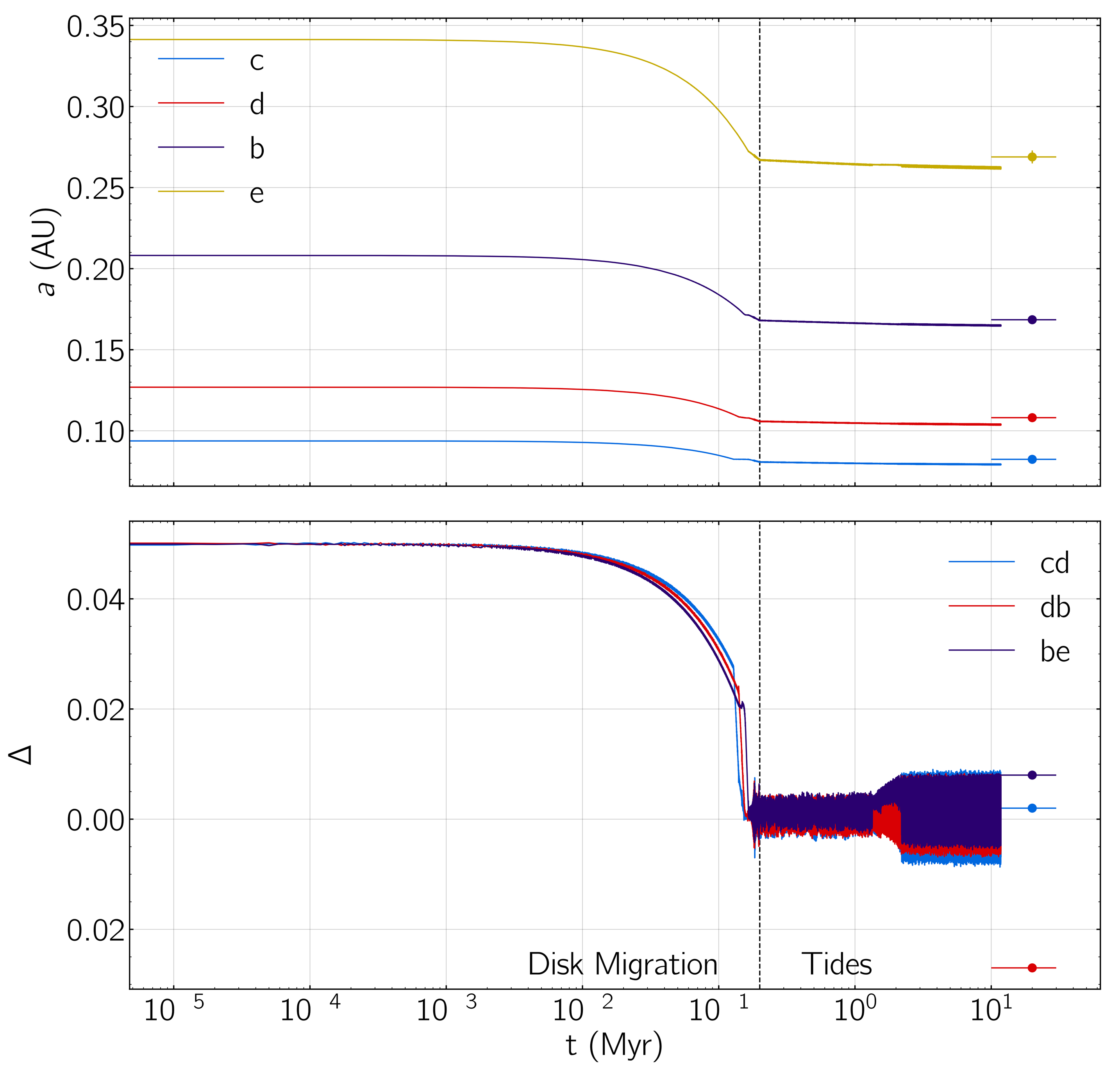
$$\Delta = \frac{\text{Observed period ratio}}{\text{Ideal period ratio}} - 1$$

Conclusions and Future Work

1. Orbital resonance is ubiquitous among young Kepler-like systems, but not in older systems. This indicates that an as-of-yet uncharacterized process disrupts these resonance chains.
2. V1298 Tau, due to its age and well-studied architecture, presents an opportunity to study a resonance chain that is actively being disrupted.
3. We propose that, during its formation, planet b was captured into a Cassini state, tilting the planet on its side and resulting in significant obliquity tides. This simultaneously explains the planet's large internal temperature and the system's broken resonance chain.

Future work to be done:

1. Continue running models to reproduce the theoretical predictions.
2. Incorporate models of tides (such as those in Millholland and Laughlin [6] or Lu et al. [7]) to directly model the obliquity evolution of V1298 Tau b.



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