The Evolution of Multiplanetary Systems With Misaligned USP Planets

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Context/Motivations

- Ultra-short period (USP) planets orbit within the magnetic truncation gap of their respective star, which has no solar system analog. They have been observed to exhibit unique dynamical parameters.

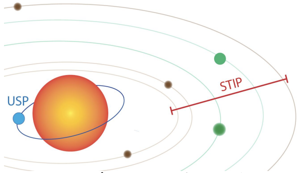

Diagram: Becker et al. 2020

- There are two known systems in which the USP planet in a multi-planet system orbits misaligned to the plane of the outer planets. One is TOI-125, where a USP planet exhibits a 14 degree misalignment from the STIP plane.
- In particular, we explore the relationship between this inclination anomaly and the stellar quadrupole moment (J2) of the host star. This is done through use of the secular perturbation theory (Murray & Dermott 1999) and through N-body simulations.
- By simulating the dynamics of the TOI-125 system, we hope to better understand the evolution of planetary systems, particularly those with misaligned USP planets, as the star spins down with time, as well as how these parameters can occur.

Secular Perturbation Theory

- The Laplace-Lagrange secular theory is used to model the complex dynamics present in planet-planet interactions by neglecting short period effects in the system, approximating the planets' orbits as a system of rings that evolve with time.
- The theory was used to better understand the effects of individual J2 values on the inclination of the four planets over time, in order to determine values of the stellar spin in which anomalies occurred.
- As can be seen in Figs. 1-2, spikes in inclination amplitude occur at two J2 values. These are caused by the "crossing" of eigenfrequencies of two of the planets in the system.

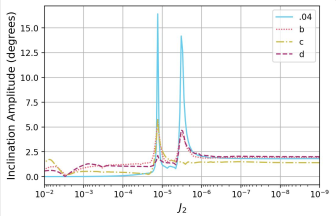

Fig. 1- Plot of inclination amplitude as a function of J2 for the TOI-125 planets using secular theory. Amplitude in this case is the difference between maximum and minimum inclination in a 10^4 year integration, and the USP planet is represented by the blue line labeled .04. The locations of the peaks in inclination allow us to determine that at these values of J2 a resonance occurs, decoupling the planets and causing them to oscillate widely in their inclination.

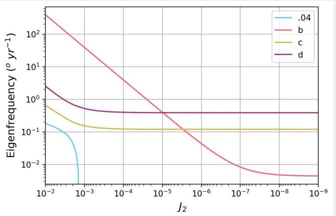

Fig. 2- Plot of eigenfrequencies of the four planets as a function of J2. A clear commensurability occurs between two of the four frequencies at two J2 values. Thus, an evolving J2 (decreasing with time, as represented in the figure) can cause natural secular resonances in the system, as the dynamics pass through these commensurabilities.

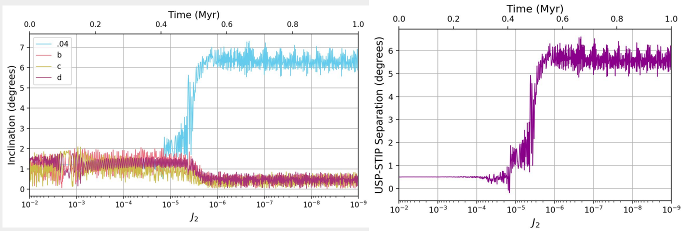

Fig. 3- Plots of a TOI-125 simulation with a 1 degree stellar obliquity. The leftmost plot represents the inclination evolution and migration of the four planets (which occurs between the instabilities found in Figs. 1-2), while the rightmost is a plot of the USP planet's misalignment from the average STIP plane.

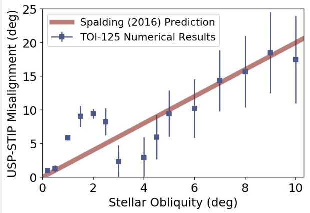

Fig. 4- Plot of USP-STIP misalignment at a J2 of 10^-8 for a variety of stellar obliquities, with the prediction from Spalding & Batygin (2016) for two planet systems overlaid. The prediction does a good job of representing the general trend of misalignment as a function of obliquity, with any variation being due to the complexity of multi-planet dynamics. Given this data, the known misalignment of TOI-125.04 of 14 degrees implies a stellar obliquity ranging between 6 and 10 degrees.

N-Body Simulation

- The N-body simulation is a numerical solution to the N-body problem. We complete these calculations using Rebound (Rein 2012) and Reboundx (Tamayo et al. 2020), and include additional forces in addition to the mutual gravitation of the planets. Additional forces included are general relativity and the gravitational harmonics (J2).
- We thus ran a one million year simulation of the system, in which J2 will decrease, as stars tend to "spin down" with age.
- The secular theory was used primarily to study the average inclination amplitudes for a given J2, in order to find the values for which the system was the most dynamically unstable; N-body sims were run with an evolving J2 to recreate the natural spin down phenomenon and observe what occurs as the star passes through these instabilities.

Conclusion/Future Work

- The increase in USP planet inclination occurs between two J2 values observed with secular theory (Fig. 1). This implies that the decoupling from the orbital plane occurs due to a natural eigenfrequency commensurability between the STIP planets, and may occur more generally.
- Secular instabilities will occur less frequently in systems with equal mass ratios, and so it is possible that this misalignment would not occur in such a system. It could however occur in systems with more extreme mass ratios, which could be in interesting case to study further.

References

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