Eccentricities and the Stability of Closely-Spaced Five-Planet Systems

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References: Smith and Lissauer (2009) [Icarus 201:381–394] | Fabrycky et al. (2014) [1202.6328] | Rowe et al. (2014) [1402.6534] | Obertas et al. (2017) [1703.08426] | Quarles and Lissauer (2018) [1801.06131]

Abstract

We investigate the stability of idealized planetary systems consisting of five one Earth mass planets orbiting a one solar mass star. All planets orbit in the same plane and in the same direction, and the planets are uniformly spaced in units of mutual Hill Sphere radii. We integrate systems where either one, or all planets begin on eccentric orbits, with eccentricities as large as 0.05 being considered. For a given initial orbital separation, larger initial eccentricity generally leads to shorter system lifetime, regardless of which planet is initially on an eccentric orbit, however systems with middle planet eccentric will have the shortest life times. The approximate trend of instability times increasing exponentially with initial orbital separation of the planets found previously for planets with initially circular orbits is also present for systems with planets initially eccentric orbits. Mean motion resonances also tend to destabilize these systems, although the decreases in system lifetimes are not as large as for initially circular orbits. For systems with all planets eccentric, we find that interestingly, they are almost as long lived as circular systems, i.e. substantially longer than systems with any one planet eccentric.

Introduction

NASA's *Kepler* mission has discovered hundreds of multiple planet systems. Many of these multi-planet systems are tightly packed, where adjacent planets' orbits can be much closer to those found in the Solar System. For instance, the Kepler-11 system harbors six known planets, five of which orbit at less than the orbital distance of Mercury from their host star. Studying the orbital stability of such tightly-packed multiple planet systems provides clues to how they form and how long they survive. The present study can be seen as an extension of Obertas et al. (2017), who investigated the stability of closely-spaced five-planet systems with the same masses and relative spacings as we use herein.

Methodology

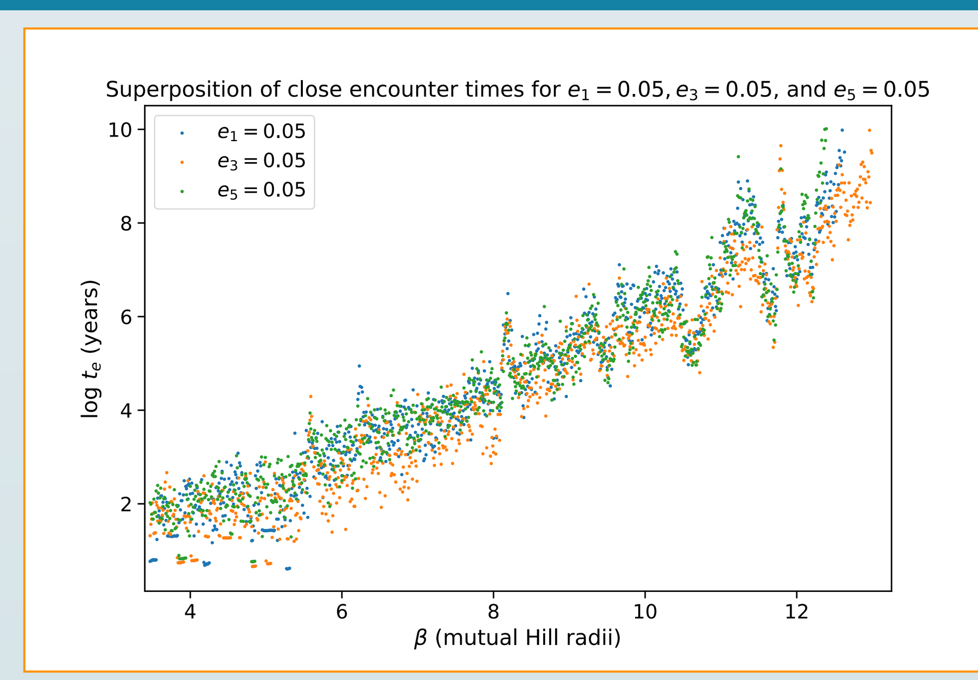
Planetary characteristics:

- five identical, 1 M⊕ planets, orbiting a 1M⊙ star in the same direction;
- initially separated by a multiple of their mutual Hill radius, defined below;
- co-planar, i.e. inclinations are zero at all times;
- initial eccentricity of one planet at either 0.01, 0.02, 0.03, or 0.05; one case of all planets eccentric at 0.05;
- initial true longitude: $2\pi n\lambda$, where λ is the golden ratio.

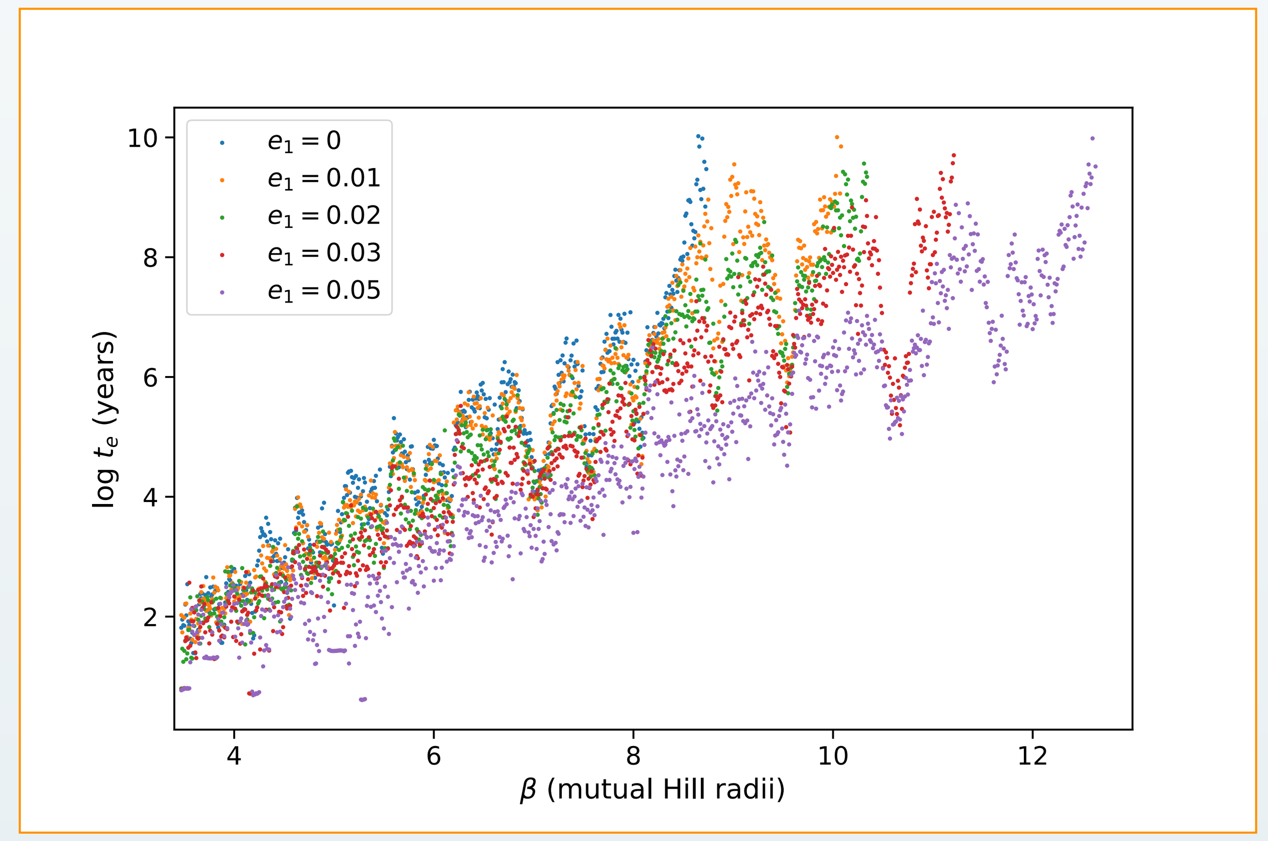
Mutual Hill radius: $R_{H_{j,j+1}} = \left(\frac{m_{j+1}+m_j}{3M}\right)^{1/3}\left(\frac{a_j+a_{j+1}}{2}\right)$

Simulation setup

- increment in β for each new simulation: 0.01
- time measured in units of Earth years;
- total number of simulations such that exactly five systems reach two billion years before either a close encounter occurs, or the run exceeds cluster compute time;
- symplectic WHFast integrator from REBOUND;
- close encounter when distance $d < 0.01$ AU.

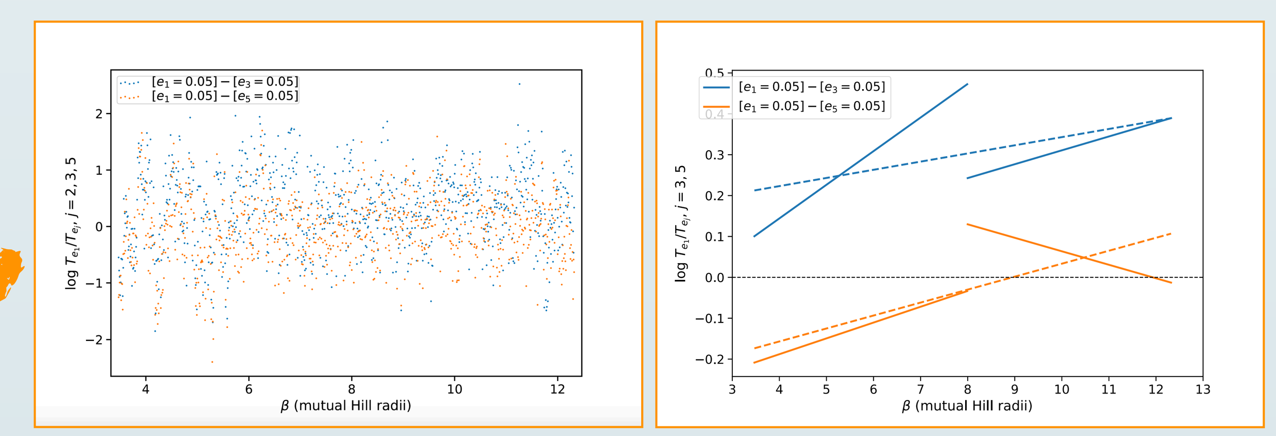


Result 1: eccentricity impact on same planet



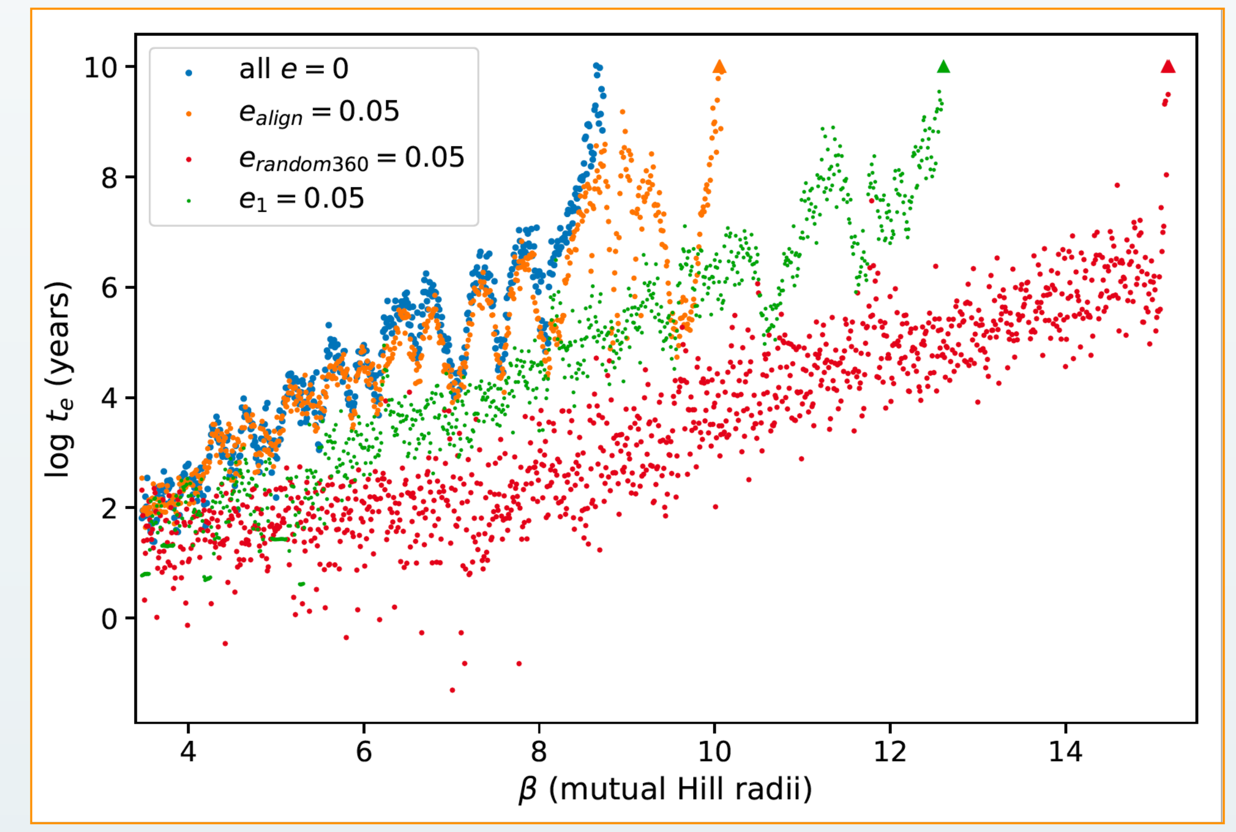
The superposition of systems with innermost planet starting at different eccentricities reveals that the higher the initial eccentricity, the shorter the life times for given initial separation. Perhaps more interestingly, the dips and peaks become less pronounced at given β as we increase the eccentricity. All cases reproduce a log-linear relationship previously known from the circular case.

Result 2: difference b/w planets with same eccentricity



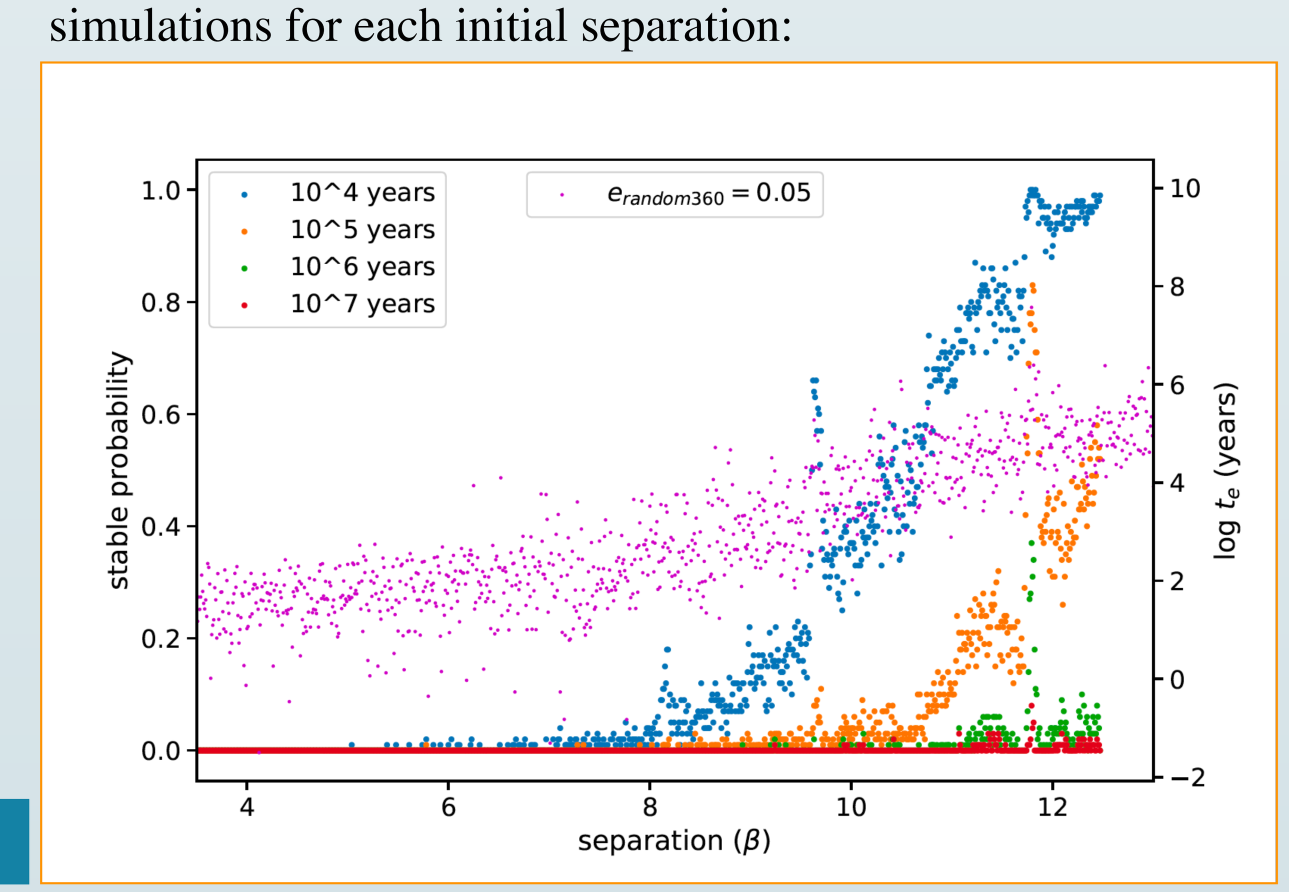
The close encounter times for the middle planet initially eccentric are substantially shorter on average than for the inner or outer planet eccentric, by a factor of about two. We also observe an increase in close encounter differences with β, compared to systems with innermost planet eccentric.

Result 3: all planets eccentric



Here, all planets begin on orbits with eccentricity 0.05, with either aligned or randomized periapses. Surprisingly, the life times of the aligned systems are similar to those of the circular ones, and thus much longer than those of systems starting out with one planet eccentric. This suggests that initial eccentricity differences between the planets are more relevant for close encounter times than the specific value of the initial eccentricity, at least for small eccentricities up to 0.05. With randomized periapses chosen within a full circle, however, we find that lifetimes are substantially reduced.

For those randomized systems, a probability of stability beyond a given timescale was computed by running 100 simulations for each initial separation:



Conclusions

We investigated closely-spaced five-planet systems starting out at different eccentricities. Even for relatively small eccentricities up to 0.05, substantial differences in close encounter times are manifest, while the log-linear behavior is preserved in all cases. Initially eccentric intermediate planets appear to make a system go unstable faster than initially eccentric inner or outer planets. Finally, larger relative (rather than absolute) eccentricities appear to be the dominant factor for shortened close encounter times in eccentric systems, unless initial periapses are chosen randomly. **(Gratia & Lissauer [1908.01117])**

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