Kozai Cycle-Tidal Friction (KCTF) Evolution of Trans-Neptunian Binaries

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Abstract

Recent observational surveys of Trans-Neptunian Binary (TNB) systems have dramatically increased the number of known mutual orbits. Our Kozai Cycle Tidal Friction (KCTF) simulations of synthetic trans-neptunian binaries show that tidal dissipation in these systems can completely reshape their original orbits. Specifically, solar torques should have dramatically accelerated the semimajor axis decay and circularization timescales of primordial (or recently excited) TNBs. As a result, an initially random distribution of TNBs in our simulations will evolve to three distinct populations: very tightly-bound systems, wider systems coplanar with their heliocentric orbit, and stable eccentric systems. The tight systems account for approximately one third of evolved systems, while a third to a half are coplanar. We also find that an initially very eccentric population ($e > 0.75$) eliminates the coplanar systems, thus fitting the currently observed orbits better.

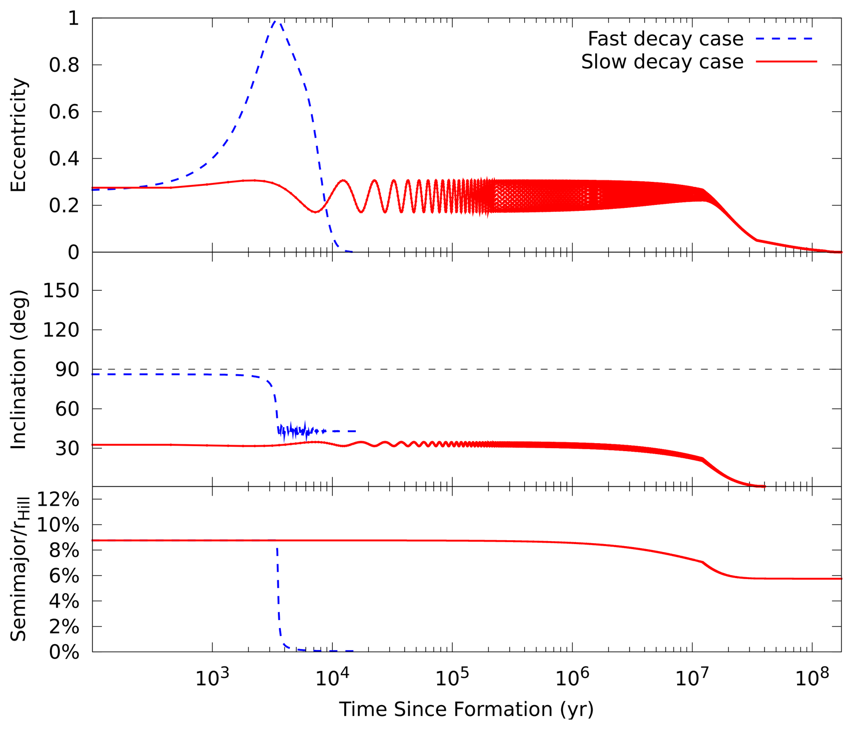

Figure 1: KCTF evolution of two TNB orbits initially differing only in inclination. The high-inclination case decays in less than 10^4 years to a very tight orbit, while the low inclination case slowly decays to wide coplanar orbit.

Methods

In order to understand how TNB orbits may have evolved since they were formed, we created a numerical Kozai Cycle and Tidal Friction model. Kozai Cycles in this context are periodic oscillations in eccentricity and inclination of the TNB mutual orbit caused by solar torques. These oscillations preserve the orbit's semimajor axis and the quantity $H_k = cos\ I \times \sqrt{1-e^2}$, where I is the inclination of the mutual orbit with respect to the heliocentric orbit and e is the eccentricity of the mutual orbit.

A significant consequence of these Kozai oscillations is that the eccentricity of the mutual orbit can become very high, especially if the initial orbit has a low eccentricity but high inclination (or vice versa). Mutual orbits with Kozai-pumped eccentricities can therefore decay due to tidal friction much faster than their initial state would imply; see Figure 1 for an example. We used a model based on [1]. [2] expanded this model by adding the capacity for the objects to have a permanent quadrupole term in their gravity field. This is more physically appropriate for solid objects (like TNOs) than the stars and giant planets for which the model in [1] was developed.

Since the model in [1] defines the evolution of the system by a set of four related inhomogeneous vector differential equations, we used a numerical integrator that could solve them rapidly and precisely on a cluster of computers. For this we choose to use a Burlisch-Stoer integrator, which combines a modified-midpoint integrator with an interpolation method to control error. To test the KCTF model, we conducted a series of Monte Carlo simulations in which we created a sample set of 1000 synthetic TNBs with randomized mutual orbital elements and system masses. We then evolved each system for 4.5 billion years, or until the system either impacted itself, became unbound, or spun to breakup.

Results

We found that most of our KCTF-evolved synthetic TNB systems evolved to either very tight orbits or orbits coplanar with the heliocentric orbit (see Figure 3). The orbits which decayed very fast due to KCTF ($< 10^7$ years) stabilized to circular orbits at less than 1% of r_{Hill} (see Figures 2 and 3). Slower-circularizing TNBs stabilized to wider orbits nearly coplanar to the heliocentric orbit. The remainder were in orbits that had a low enough initial H_k that they never reached high enough eccentricity to experience KCTF decay, or were trapped by obliquity tides. The relative fraction of these three populations is given in Table 1.

The vast majority of the coplanar population result from low initial eccentricities ($e < 0.5$), and do extend into observable separations. Since wide, coplanar orbits have not been observed, this may imply that TNBs formed in initially eccentric orbits. Low delta-v captures do tend to produce eccentric orbits, and the capture simulations of [3] almost exclusively produced initial orbits with eccentricities greater than 0.8. Alternatively, wide coplanar orbits (>5% r_{Hill}) are especially susceptible to impact disruption [4]. In addition, there is an observational bias against low-inclination orbits, as it much harder to determine their orbits.

KCTF preserves the prograde/retrograde ratio of the initial distribution. A retrograde preference for binaries formed by the L^2S capture method was predicted by [5]. On the other hand, the gravitational collapse method in [6] favors orbits in the direction of disk clump rotation, which simulations (cited therein) generally show as prograde. The current inclination distribution could therefore serve as a tracer for these various formation methods.

Some simulations were also run at much lower initial rotation rates, which increased the fraction of systems that decayed to tight orbits, as the objects required less momentum transfer to become aligned with the orbital axes. The effect of adding a significant gravitational J_2 was to minimize the variation due to the tidal properties of the binary systems.

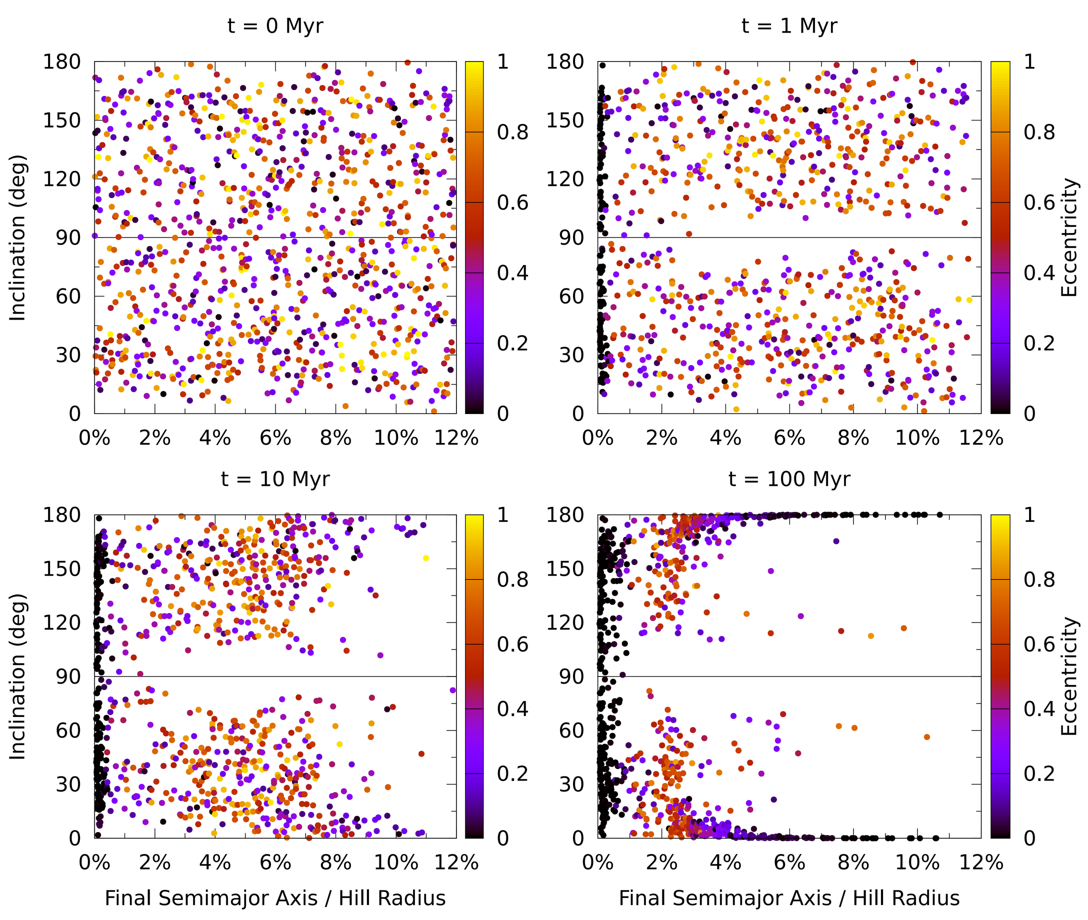

Figure 2: The time evolution of synthetic orbits for equal-mass TNBs with Q=100 and J_2=0.01.

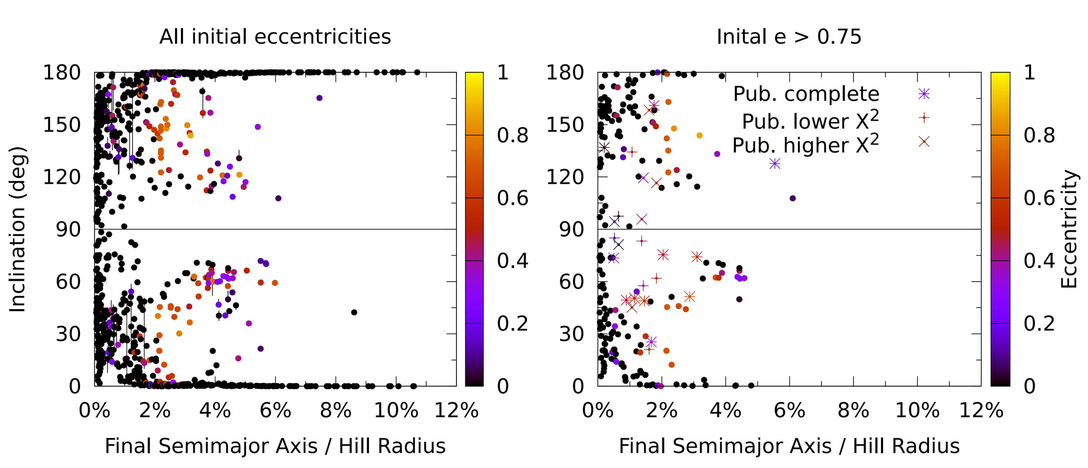

Figure 3: Left: The final post-KCTF orbits for equal-mass TNBs with Q=100 and J_2=0.01; vertical lines indicate the inclination range of orbits that did circularize in 4.5 Ga. **Right:** The same, but excluding any orbits with initial $e < 0.75$. Also, published orbits are displayed for comparison.

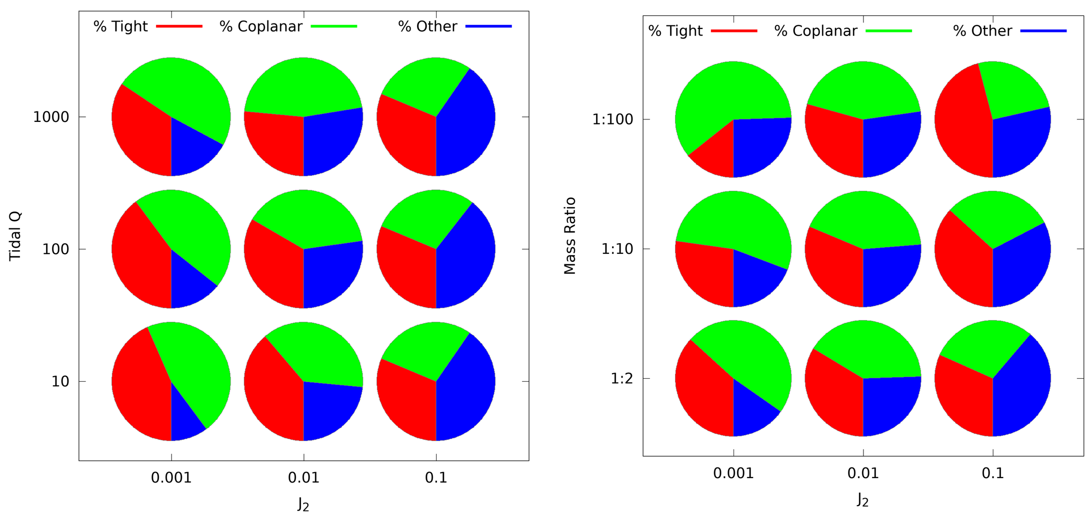

Figure 4: The effects of Q, J_2, and mass ratio on the results of the simulations. "% Tight" are systems with a final semimajor axis of $< 1\% r_{Hill}$. "% Coplanar" are systems with a final inclination of $< 5°$.

Conclusions

KCTF can significantly transform the orbits of trans-neptunian binaries. At least 90% of random synthetic TNB systems survive 4.5 Ga of KCTF evolution. A third of the surviving TNB systems decay to less than 1% of their mutual Hill radius. A further third-to-half decay to wider, circular orbits within 5° of heliocentric orbit. All resulting systems preserve their initial prograde/retrograde preference. Most systems circularize, but obliquity tides can keep some eccentric.

Large J_2 moments minimize the effects of varying tidal Q. Slower initial rotation rates increased the fraction of highly-evolved systems. Higher mass ratios enhanced the fraction of tight systems for high J_2, while reducing the fraction for low J_2. In addition, high mass ratio systems (100:1) had a lower survival rate due to the secondary impacting the primary in a third of cases.

The observed distribution of TNBs does not appear to contain the coplanar population seen from KCTF. This could be explained by collisional disruption, an initially very eccentric population, or some combination of both. In the case of initially eccentric TNB orbits, $e > 0.75$ is a sufficient condition to eliminate the coplanar population.

A digital copy of this poster can be obtained from: http://www.lowell.edu/~porter/TNO-KCTFposter.pdf

See Also: Exomoons

KCTF's ability to rapidly circularize and shrink satellite orbits can also help in stabilizing large moons of migrating giant exoplanets. Specifically, an exomoon captured around a habitable-zone giant planet can evolve to a close circular orbit. An Earth-to-Titan sized exomoon in a loose eccentric orbit will evolve to a stable orbit in roughly half of all cases. The resulting orbits should be detectable by transit variations and other methods, with timing variations of up to 60 minutes. For more, see below:

http://adsabs.harvard.edu/abs/2011ApJ...736L..14P

References

[1] P. P. Eggleton and L. Kiseleva-Eggleton. Orbital Evolution in Binary and Triple Stars, with an Application to SS Lacertae. ApJ, 562:1012–1030, December 2001.

[2] D. A. Ragozzine. *Orbital dynamics of Kuiper Belt object satellites, a Kuiper Belt family, and extra-solar planet interiors*. PhD dissertation, California Institute of Technology, 2009.

[3] Y. Funato, J. Makino, P. Hut, E. Kokubo, and D. Kinoshita. The formation of Kuiper-belt binaries through exchange reactions. Nature, 427:518–520, February 2004.

[4] D. Nesvorný, D. Vokrouhlický, W. F. Bottke, K. Noll, and H. F. Levison. Observed Binary Fraction Sets Limits on the Extent of Collisional Grinding in the Kuiper Belt. AJ, 141:141–159, May 2011.

[5] H. E. Schlichting and R. Sari. The Ratio of Retrograde to Prograde Orbits: A Test for Kuiper Belt Binary Formation Theories. ApJ, 686:741–747, October 2008.

[6] D. Nesvorný, A. N. Youdin, and D. C. Richardson. Formation of Kuiper Belt Binaries by Gravitational Collapse. AJ, 140:785–793, September 2010.