KCTF Evolution of Trans-Neptunian Binaries: Connecting Formation to Observation

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Abstract

Recent observational surveys of Trans-Neptunian Binary systems have dramatically increased the number of known mutual orbits. Knowledge of these orbits potentially offers way to determine their primary method of formation, which in turn places constraints on other aspects of the early solar system. However, Kozai Cycle Tidal Friction (KCTF) simulations of synthetic binary systems shows that tidal dissipation in these systems is very significant, even assuming Q=100. We therefore infer that the currently-observed distribution of binary TNO mutual orbits is probably not representative of their original state. Indeed, an initial distribution with high eccentricity and uniform-distributed semimajor axes appears to (non-exclusively) fit these criteria.

1. Motivation

TRANS-NEPTUNIAN Binary systems (TNBs) constitute approximately 10% of the objects between 30 and 70 AU, and up to 30% of the Cold Classical Kuiper Belt [8]. Being much further from the Sun than the Asteroid Belt, TNBs have wider Hill Radii (≈16 times larger) than their inner solar system counterparts, and have only limited planetary perturbations (especially the cold classical belt). In addition, the larger mass distribution of TNOs increases the number of observable binary systems enough to allow preliminary statistical measurements. Mutual orbits have been reported (or will shortly be reported) for 24 objects (c.f. [4]), and separations at discovery for at least 36 more. The known orbits provide directly their semimajor axis over their Hill radius (a/r_{Hill}), while the other systems can be estimated by assuming an albedo and density. Assuming an albedo of 0.1 and density 1.0 g/cm^3 for the TNBs without orbits, the observed binary systems follow the distribution seen in Figure 3.

These observations show that the majority of detected TNB systems have a separation of less than 2% of a/r_{Hill}, with most of the systems between 0.3-1.0%. Even more striking is the apparent lack of widely-separated systems, which should be easier to detect. Clearly then, TNBs are generally in close mutual orbits. But how close is close? The current inner cut-off is a function of observational technology (limits of HST and Keck AO resolution), raising the question of whether the upward trend will continue as higher-resolution instruments come online. Since the solar flux is so much lower (≈250 times smaller) than the asteroid belt, the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect cannot significantly spin up TNOs, causing fission and a close binary. The more likely methods, therefore, are collisions and dynamical captures. Collisions are thought to produce binaries at the lower end of this range (e.g. Pluto-Charon at 0.31%), while captures should be more random, and fill out the almost-empty area $>$2%. Explaining this distribution therefore requires either that captures were much rarer than collisions (which seems dynamically unlikely) or some form of post-capture orbital evolution. Since more common models of tidal evolution assume high primary/secondary mass ratios (rather than the near-unity ratios observed) and minimal solar torques, we chose a more complex model which combined Kozai cycles and mutual tidal friction. We then inputed an array of synthetic binary systems into the model and attempted to reproduce the observed distribution of separations.

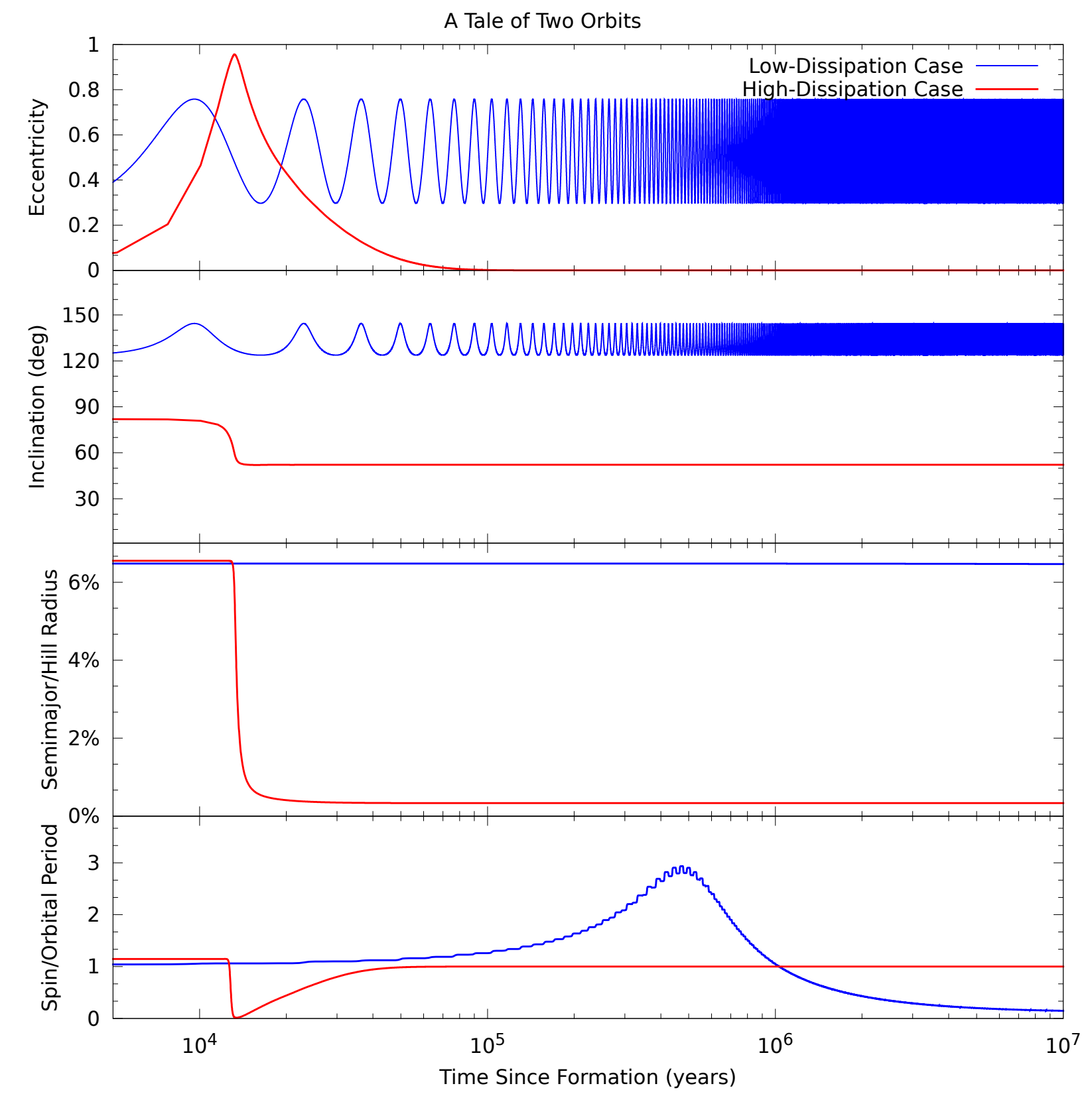

Figure 1: *Plot comparing the KCTF evolution of two orbits initially similar, but which diverge due to the orbit in red having a larger Kozai amplitude, thus allowing for much greater tidal dissipation.*

2. KCTF Model

In order to understand how TNB orbits may evolve since they were formed, we created a numerical Kozai Cycle and Tidal Friction (KCTF) model. Kozai Cycles in this context are the 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 $H_k = cos(I_{helio}) \times \sqrt{1-e^2}$, where I_{helio} is the inclination of the mutual orbit from the heliocentric orbit. The periods for these oscillations are between ≈2 kyr and 2 Myr. The eccentricity of the mutual orbit in these oscillations can become very high, and since tidal friction has a much faster drop-off than inverse square, these Kozai-pumped eccentricities can decay due to tidal friction much faster than their initial state would imply. Figure 1 shows this process in both a high-dissipation case and a low-dissipation case. This KCTF process has been previously identified as significant [6], but only demonstrated for the Orcus-Vanth system [7]. We used a similar Eggleton & Kiseleva-Eggleton [1] model to [7], though with a Burlisch-Stoer integrator. This model directly evolves the mutual orbital elements and spins of the binary while holding the heliocentric orbit constant. We did not include any dynamical effects from objects external to the binary other than the Sun.

3. Monte Carlo Simulations

To test the KCTF model, we then began a series of Monte Carlo simulations in which we create a sample set of synthetic TNBs with randomized mutual orbital elements and fixed physical properties and heliocentric orbit. We then evolved each system for either 3.0 billion years or until the system became static in a and e. Figure 2 shows the results for ≈1300 simulations of a Borasisi-Pabu-like binary with Q=100. The top plane includes all the synthetic systems, and shows three distinct populations. Systems which remain at their original separation have a small Kozai amplitude, implying the initial orbit had both low inclination and eccentricity. In contrast, the systems which decayed to the bottom of the plot had either large initial eccentricity or a large Kozai amplitude (which pumped up the eccentricity). These high-dissipation systems tend to cluster in very circular orbits at around 0.35-0.5% of the Hill radius. At this distance, the tidal forces are strong enough to quickly circularize the orbits, but not to reduce the orbit's semimajor axis. Orbits with an initial periapse below this distance ($<$7% of cases) can shrink even farther, but such cases generally lead to merger of the two bodies. The third population represents systems that are decaying, but at slower rate than the high-dissipation TNBs.

However, as Figure 3 shows, the observed distribution of binary separations is heavily weighted to tighter orbits. The uniform input distribution therefore creates too many systems which remain at their original separations. This implies that either TNBs formed uniformly and and were affected by some other process (i.e. dynamical hardening) or they formed in generally eccentric orbits. We tested the latter case by subsampling the synthetic TNBs that had an initial eccentricity greater than 0.7. This produced a final distribution much closer to the observed, without requiring any other process. Figure 4 repeats the simulations in Figure 3, but with a tidal dissipation constant Q=10, rather than Q=100. Even with an order of magnitude change in Q, the final distributions are only slightly changed. Since Q=100 corresponds to a solid body, Figure 3 provides a conservative estimate of the amount of orbital decay, while Figure 4 is potentially more realistic. However, the similarity of the two simulations shows that the overall KCTF process is mostly independent of material strength.

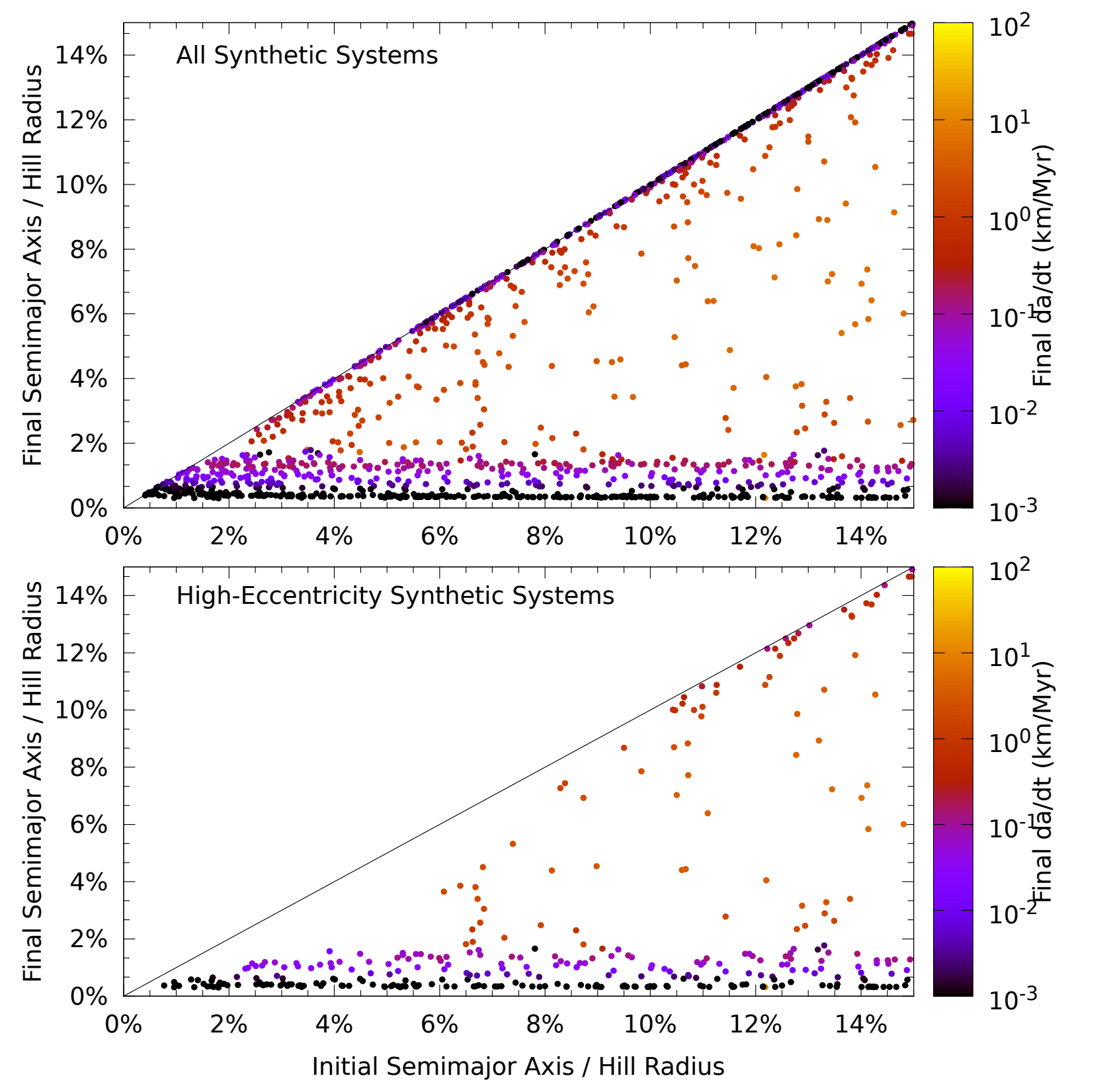

Figure 2: *Plots showing the evolution of synthetic binary TNO systems, color-coded to match dissipation rate at the end of the simulation. The top includes all systems, and the bottom includes only those with initial* $e > 0.7$.

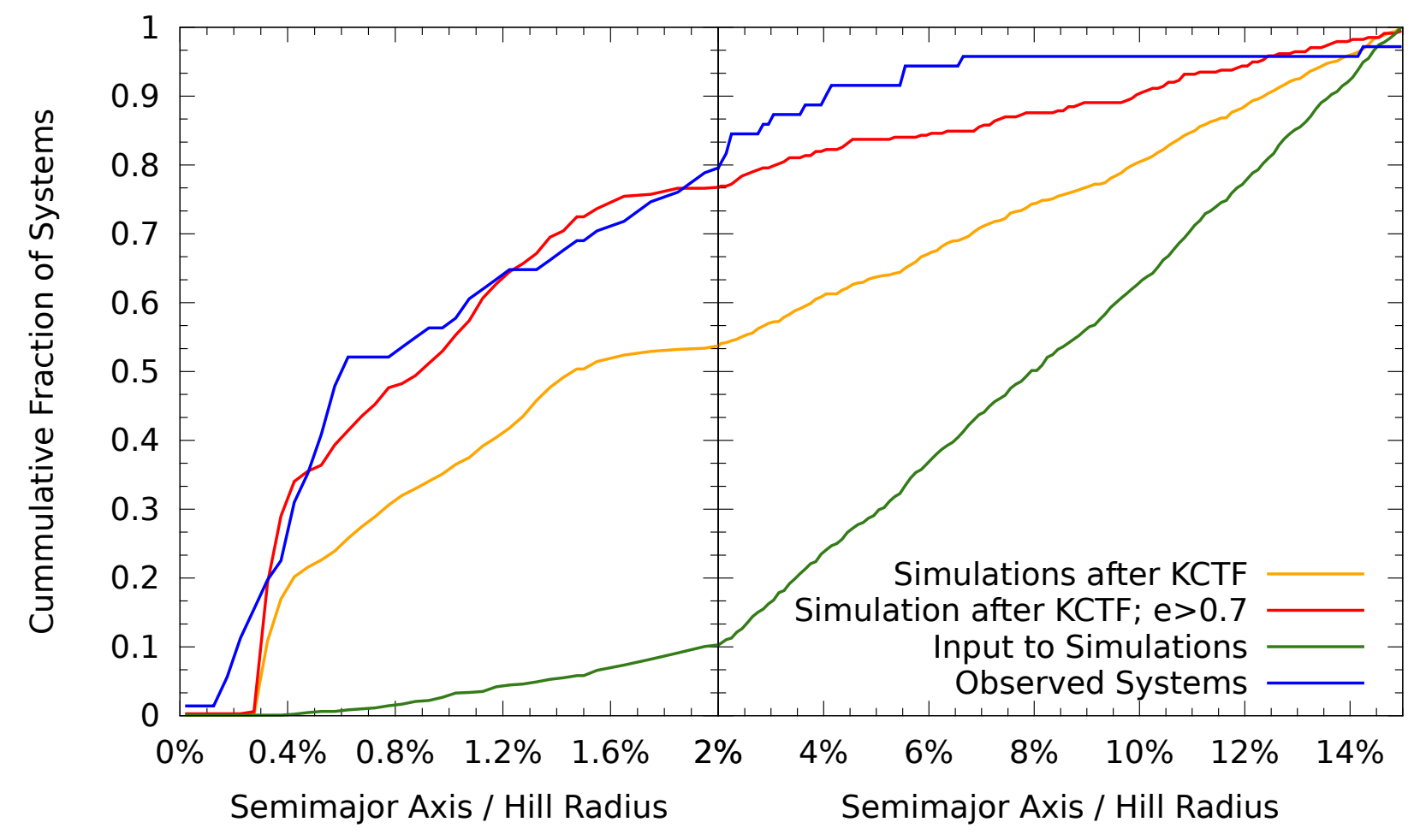

Figure 3: *Cumulative distribution plot of observed and simulated binary TNO systems with Q=100. Excluding synthetic systems with initial eccentricity below 0.7 appears to fit the observed data better, implying that capture may be the dominant binary formation mechanism.*

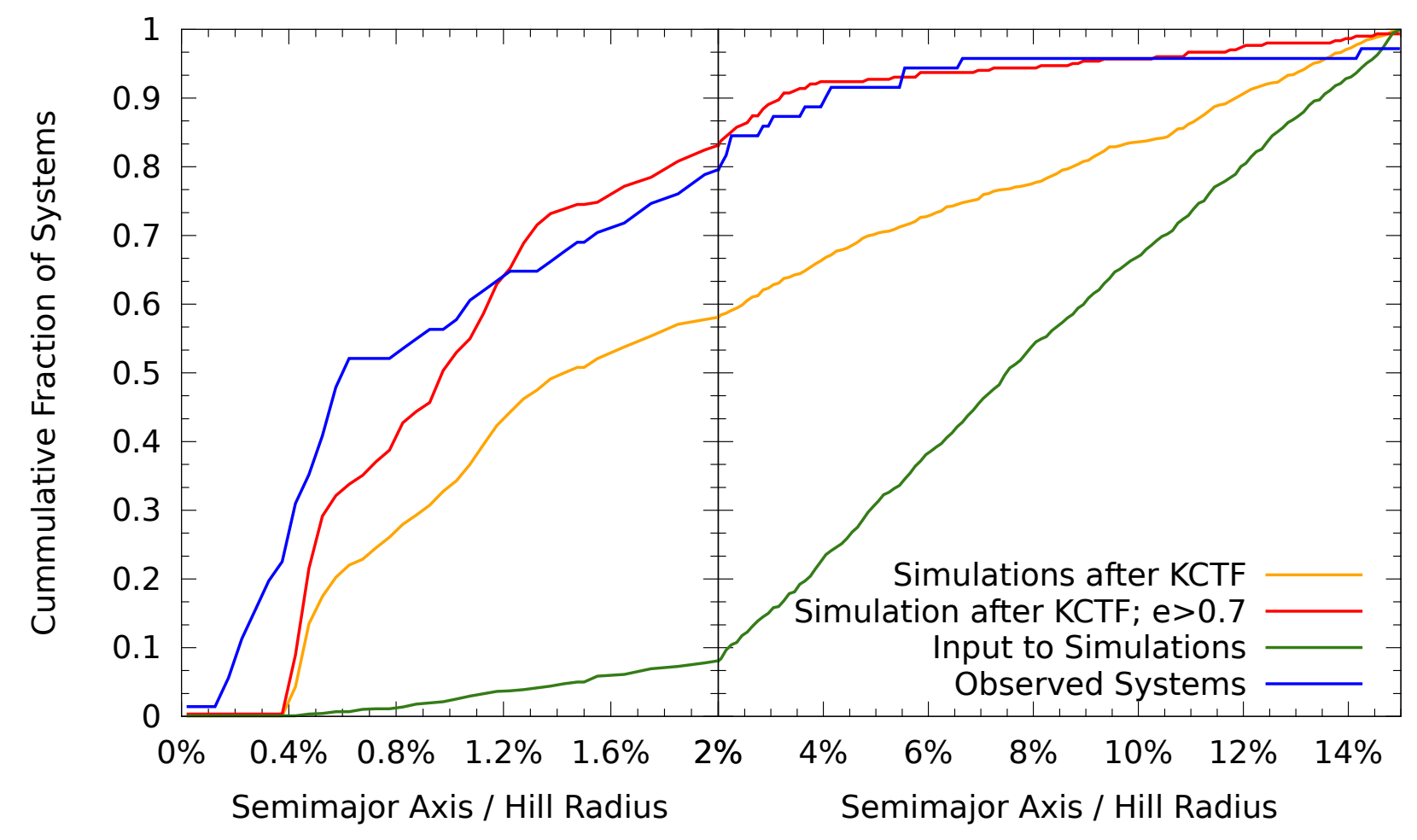

Figure 4: *The same simulations as in Figure 3, but with Q=10.*

4. Discussion

Several general conclusions can therefore be drawn from our simulations:

1. The currently-observed distribution of binary TNO mutual orbits is probably not representative of their original state.
2. Binary formation mechanisms must therefore be tuned to fit distributions which can evolve into the observed state.
3. A formation mechanism that produces high eccentricity orbits can more easily fit the observed systems, though low eccentricity methods may still be plausible.

Several different formation pathways for similar-mass binary TNOs have been proposed, but most of them attempt to fit the orbits of observed. Clearly, KCTF evolution makes such assumptions more difficult. Indeed, high-eccentricity formation methods (momentum exchange [2], for example) had often been discounted as unphysical, whereas our simulations would imply that they are potentially more plausible than moderate-eccentricity formation modes (like gravitational collapse [5]). We also show that dynamical hardening by passing TNOs (i.e. the L^{2}s method [3]) is not required to shrink most mutual orbits, but could still be influential on orbits with low Kozai amplitudes.

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