2. KCF Model

In order to understand how TNB orbits may evolve since they were formed, we created a numerical Kozai Cycle and Tidal Friction (KCF) 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 $a/R_{\text{Hill}} = \sin(i) \cos(\omega) / \sqrt{1 - e^2}$, where $i$ is the inclination of the mutual orbit from the heliocentric orbit. The periods for these oscillations are between $\approx 2$ Myr 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 2 shows this process in both a high-dissipation case and a low-dissipation case. This KCF process has been previously identified as significant [5], but only demonstrated for orbits [6]. We used a similar Egginton & Kiseleva-Eggleton [1] model to [6], though with a Burulis-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 KCF model, we then began a series of Monte Carlo simulations in which we create a sample set of synthetic TNB 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 $a \approx 1300$ 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 large initial eccentricity or a large Kozai amplitude (which pumped up the eccentricity). These high-dissipation systems tend to cluster in nearly 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. Since these systems are at or beyond the current limit of detection, further observations are required to determine how common they really are. 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 lighter orbits. The uniform input distribution therefore creates too many systems which remain at their original separations. This implies that either TNBs formed uniformly and were affected by some other process (i.e. dynamical hardening) or they formed in generally eccentric orbits. We tested the latter case by filtering out the synthetic TNB runs that had an initial eccentricity less 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.

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.

4. Further observations of TNBs will allow for much more precise estimations of TNB evolution, and thus the original state of the Kuiper Belt.

Several different formation pathways for similar-mass TNOs have been proposed, but most of them attempt to fit the current orbits of observed TNBs. Clearly, KCF 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. We also show that dynamical hardening by passing TNOs (i.e. the L1’s method [3]) is not required to shrink most mutual orbits, but could still be influential on orbits with low Kozai amplitudes.

References


