Chapter 5

On the Tidal Evolution of Kuiper Belt Binaries

Abstract

The formation and evolution of binary Kuiper belt objects (KBOs) is closely intertwined with the history of the outer solar system. The interpretation of the currently observed characteristics of these binaries must include an understanding of effects that can significantly modify their orbital properties. Two major sources of potential modification include tidal dissipation and perturbations from the Sun. As a first step in understanding these effects, we describe the results of a new orbital evolution model that accounts for tidal dissipation at arbitrary eccentricity, the importance of Kozai cycles induced by the Sun, and orbital precession due to non-hydrostatic asymmetries of small solid bodies. In particular, we find that Kozai Cycles with Tidal Friction (KCTF) can significantly shrink the orbits of KBO binaries and may produce systems that would otherwise appear to be formed by collisions, with the Orcus-Vanth binary as the primary example. The unique observational signatures of KCTF are discussed along with other consequences of orbital and tidal evolution of KBO binary orbits.

5.1 Introduction

Investigating the origins of binary Kuiper belt objects (KBOs) holds significant promise for improving our understanding of the formation of the outer solar system. Although only ∼60 KBO binaries are known, with only ∼20 well-characterized orbits, there are already several observational trends that may be unique clues into processes active in the early solar system (Noll et al., 2008a,b). Brown et al. (2006) found that the binary fraction of large KBOs is significantly higher than the binary fraction of smaller KBOs, a result which continues to be true as more binaries are found (Brown, 2008). Noll et al. (2008b) recently reported that the binary fraction of non-resonant KBOs with low heliocentric inclinations ($29.3 \pm^{7.2}_{6.3}$ %) is strikingly different from the binary fraction of high inclination KBOs of similar sizes ($2.9 \pm^{6.5}_{2.4}$ %). Since there is also a strong trend of increasing binary frequency at small separations (Noll et al., 2008a), these binary fractions are certainly underestimates since the observations cannot resolve binaries at the smallest separations. The relative brightness of binary components is heavily skewed towards equal-brightness binaries, a result that appears to be robust despite some observational bias (Noll et al., 2008a). Finally, Benecchi et al. (2009) have found that the visible colors of KBO binary components are the same, even though the range of colors is as large as the range of colors for (apparently) single objects.

To describe the wide range of binaries, two general classes of binary formation mechanisms have been proposed, which we call the collision and capture mechanisms. Small satellites of large KBOs appear to be formed by collision, as proposed for the Pluto (Canup, 2005; Stern et al., 2006) and Haumea (Ragozzine & Brown, 2009) systems. Smaller KBO binaries appear to have more angular momentum than can be generated in typical impacts and are apparently formed by some other mechanism which does not involve direct contact (e.g., Weidenschilling, 2002; Goldreich et al., 2002; Funato et al., 2004; Astakhov et al., 2005; Nesvorny, 2008). All proposed mechanisms of binary formation require higher number densities than present in the current Kuiper belt and were mostly active in the dynamically cold primordial planetesimal disk. Later excitation of this primordial disk sculpted the Kuiper belt seen today (e.g., Morbidelli et al., 2008). The two different models of binary formation predict different kinds of binaries. Collisionally-formed binaries will have low angular momenta and an isotropic inclination distribution (since the final inclination is given mostly by the random impact location). Binaries formed through capture will have higher amounts of angular momentum and a more bimodal inclination distribution around $i \simeq 0^\circ, 180^\circ$ (Schlichting & Sari, 2008b). In some regards, the two different binary formation mechanisms map well to the two different classes of binaries, with small satellites in tight circular orbits around large KBOs formed by collision and equal mass binaries with wide orbits formed by capture. Nevertheless, several important details require further investigation.

In particular, the current orbital properties of KBOs may not represent the initial orbital distribution. Without a clear understanding of the processes that can modify KBO binary orbits, there is no sure way to extrapolate the present-day observational trends backwards in time in order to gain insights into binary formation mechanisms. Potentially important processes that can modify KBO binary orbits include: 1) close interactions with the giant planets that transported KBOs from the primordial planetesimal disk to their current position in an excited Kuiper belt; 2) interactions with passing and colliding KBOs both early in the solar system and in the present-day Kuiper belt (Stern et al., 2003; Collins & Sari, 2008); 3) orbital perturbations of the binary orbit due to the planets and the Sun (Perets & Naoz, 2008, hereafter PN09); and 4) tidal interactions that can change binary orbital elements over long timescales. In this work, we undertake a preliminary investigation of the last two processes, specifically the orbital and tidal evolution of KBO binaries, including perturbations from the Sun. We note that many of the same techniques and results are relevant to the orbital evolution of asteroid binaries (PN09).

The tidal evolution of KBO binaries is not like the tidal evolution of planetary satellites and requires a substantially different approach. The main reasons for these differences in KBO binaries including the following, some of which were pointed out by Noll et al. (2008a).

- In many KBO binaries, the primary and secondary are of comparable size. Most discussions and derivations of tidal evolution assume one object is much larger than the other.
- The eccentricities of these systems can be relatively high ($e \gtrsim 0.2$), requiring the use of oft-neglected higher-order terms in the tidal evolution equations (e.g., Wisdom, 2008).
- The ratio of the strength of primary and secondary tides may be unlike other systems, leading to atypical results. For example, tides in a fast-spinning primary may easily be strong enough to cause the orbital eccentricity to grow in time, unlike the the typical decrease in eccentricity that is usually expected.
- The tidal dissipation parameters (k_2 and Q, described below) are unconstrained for these icy bodies even to within an order of magnitude.

For the above reasons, the tidal evolution of KBO binaries has not been modeled in any significant detail, with the exceptions of early studies of the Pluto-Charon system (e.g., Dobrovolskis et al., 1997), recent studies of how Pluto's small additional moons Nix and Hydra can be placed into the tidal evolution story, and a study of the evolution of Eris-Dysnomia system (Greenberg & Barnes, 2008, hereafter GB08). The purpose of the present paper is to take the next steps in modeling the tidal evolution of these binaries. Our goal is not necessarily to accurately reproduce the exact tidal history of any particular pair. Rather, we are aiming to develop a self-consistent general model which can explore a wide variety of physically-plausible tidal histories. Imperfections in the model must be understood in this context.

We will use the Orcus-Vanth binary (Brown et al., 2009) as a case study for investigating the tidal evolutionary histories of KBO binaries. This interesting binary is the focus of this chapter because this system falls in an intermediate regime between the two types of KBO binaries: Orcus is an intermediate size KBO (500 km radius) with an intermediate binary mass ratio (few percent). While there are indications that this system formed by collision, we show below that it is possible to reproduce the current orbital characteristics by starting on a wider orbit typical of capture binaries. Though the majority of this chapter focuses on this system, many of the results are generally applicable to KBO binaries as well as asteroid binaries (PN09).

Did the Orcus-Vanth system form by collision or capture? To answer this question, we will need to understand tidal evolution of KBO binaries at arbitrary eccentricities and mass ratios. Using the orbital and tidal evolution framework of (Eggleton & Kiseleva-Eggleton, 2001), with modifications relevant to small solid bodies, we can make preliminary investigations into important processes that may have significantly modified the orbital characteristics of KBO binaries since their formation.

We will first discuss the collisional model, including tidal evolution outwards from near the Roche lobe. This is followed by general considerations of tidal evolution inwards from a wider capture-like orbit. We then show how adding perturbations from the Sun can induce Kozai cycles which, combined with tidal friction, can significantly shrink orbital separations. The orbital and tidal evolution model is then introdcued, with full model details given in the Appendix. Applying this model to Orcus and Vanth, we find that the current properties of this system can be reached from a wide variety of initial orbits. Finally, we discuss the potentially observable signatures of this evolution and the general implications of our results on the study of KBO binaries.

5.2 Collisional Formation and Tidal Evolution Outwards

5.2.1 Parameters of the Orcus-Vanth System

The total mass of the Orcus-Vanth system was determined from Kepler's third law by Brown et al. (2009) to be $M_{tot} \equiv m_1 + m_2 = 6.36 \pm 0.06 \times 10^{20}$ kg. Stansberry et al. (2008) use thermal modeling of *Spitzer* data to find that the radius of Orcus is about 473 ± 37 km. These authors did not account for the presence of the unresolved satellite, which has a fractional brightness in the visible of about 8% (Brown, 2008). Using this range of radii yields a density for Orcus of $1.4^{+0.4}_{-0.3}$ g cm^{-3}, where the error is entirely dominated by the radius error. The albedo of Orcus is about 20%. Assuming that Vanth and Orcus have the same albedos and densities, a brightness ratio of 8% corresponds to a mass ratio of $0.08^{3/2} = 0.023$. However, the albedo of Vanth could be up to 5 times higher or lower than the albedo of Orcus and its density may be lower by a factor of $\sim$2. This leads to a wide range of theoretically possible mass ratios from 0.001 (high albedo, low density) to 0.25 (low albedo, same density). Similarly, the radius of the satellite could range from 60 to 300 kilometers.

While it is unlikely that Vanth occupies either extreme of these ranges, its mass ratio and radius are quite uncertain. Except where noted, we will use the following parameters for the Orcus-Vanth system: $m_1 = 6.21 \times 10^{20}$ kg, $\mu \equiv m_2/m_1 = 0.023$, $R_1 = 473$ km, $R_2 = 134$ km, and $\rho = 1.4$ g cm^{-3}. (Note that we use μ for the mass ratio instead of the reduced mass and we reserve the symbol q to mean the orbital periapse distance.) The orbital parameters determined by Brown et al. (2009) are a semi-major axis of $a = 8985$ km and an eccentricity upper-limit of $e < 0.003$. The current heliocentric orbital parameters are typical for an excited Plutino with $a_{\rm helio} = 39.3$ AU, $e_{\rm helio} = 0.222$, and $i_{\rm helio} = 20.6°$.

In our consideration of tidal evolution, we will also need to estimate the relevant tidal parameters for Orcus and Vanth: the Love number, k_2 (which describes the response of the material to a second-order potential) and the tidal dissipation parameter, Q (which describes the fraction of total energy dissipated during tidal flexure). The value of Q is not well known, but is often assumed to be $\sim$100 for terrestrial and icy bodies (Goldreich & Soter, 1966). A standard way for estimating k_2 is to use the relation derived from comparing material strength to self-gravity (Goldreich & Soter, 1966):

$$k_2 \approx \frac{3/2}{1 + \frac{19\mu_r R}{2\rho G M}} \tag{5.1}$$

where μ_r is the rigidity of the body, typically assumed to be 4 $\times 10^9$ N-m for ice, but which could easily vary by orders of magnitude. Using the nominal parameters, we find that $k_{2,\rm Orcus} \simeq 0.0048$ and $k_{2,\rm Vanth} \simeq 0.0004$, e.g., low k_2 values typical of small rigid bodies. For small KBO binaries that are rubble piles, e.g., which have significant void space on the interior, the analysis of Goldreich & Sari (2009) implies that k_2 can be enhanced, particularly when the objects are small ($R \lesssim 100$ km). Many small KBOs are thought to have significant porosity, as inferred from low densities, and tidal evolution may be quite enhanced in these bodies. Orcus and Vanth are relatively large KBOs, so we will neglect these effects.

5.2.2 Tidal Evolution Outwards

Suppose that Orcus-Vanth family formed in a collision. In this sense, the system would resemble the Pluto-Charon system. Canup (2005), who modeled the Pluto-Charon collision in detail, suggested that the normalized angular momentum, $J \equiv L/L'$, is a useful criterion for understanding the formation of a binary, where L is the current orbital and spin angular momentum and $L' \equiv \sqrt{GM_{tot}R_{12}}$ where R_{12} is the radius of an equivalent spherical object containing the total system mass, M_{tot}. Applying this to the Orcus-Vanth system, assuming that both objects are spinning at the orbital frequency ($P = 9.58$ days) and using the nominal mass ratio, we find $J = 0.1$; the relatively low value (e.g., $J \lesssim 0.4$) indicates that the angular momentum budget can be readily achieved in a sub-catastrophic collision. In fact, the mass ratio and normalized angular momentum of Orucs-Vanth are very similar to the Earth-Moon system ($\mu_{EM} = 0.012$ and $J_{EM} = 0.11$) for which formation by giant impact is preferred. However, we must note that the full range of possible mass ratios allows for a wide variety of J values from $J \simeq 0.01$ for a high albedo satellite to $J \simeq 0.7$ for a low albedo satellite. This wide range results from the total orbital angular momentum, which generally dominates the spin angular momentum:

$$L_{\rm orb} = \frac{m_1 m_2}{m_1 + m_2}\sqrt{G(m_1+m_2)a(1-e^2)} = \frac{\mu}{1+\mu^2} M_{tot}\sqrt{GM_{tot}a(1-e^2)} \tag{5.2}$$

where the second equality shows the dependence to the unknown mass ratio. If Vanth's albedo is three times smaller than Orcus, then $q \simeq 0.1$ and $J \simeq 0.37$, which is very similar to the normalized angular momentum of Pluto and Charon; $J_{PC} = 0.38$ using the most recent values for the Pluto-Charon system (Tholen et al., 2008). Canup (2005) finds a variety of SPH models for the giant impact formation of Pluto-Charon that are able to reproduce both the relatively large mass ratio $q > 0.1$ and a normalized angular momentum of $J \sim 0.4$. These models involve equal-mass impactors with high impact parameters and it seems that binaries with $J > 0.4$ cannot be effectively created in non-catastrophic collisions.

In the collision model, Vanth was initially in a nearly circular orbit, coplanar with the equator of Orcus, with a semimajor axis just beyond the Roche limit ($\sim 3R_p$). As in the case of Haumea, the post-collision Orcus should be rapidly rotating from the collision. Tidal torques would then transfer angular momentum from Orcus' spin to the binary orbit. (Vanth's spin angular momentum is also contributed to the orbit, but this effect is relatively small.) Vanth's orbit would continue to expand until the spin rate of Orcus reached the orbital frequency and Orcus and Vanth attained the double synchronous state (DSS). Most systems tidally evolve towards DSS, though it may not be a stable end-state for some systems (e.g., when the spin rate is slower than the initial orbital frequency, in which case the end state is often an inward spiral). Whether DSS is actually achieved during the age of the solar system depends on the rate of tidal evolution. Since the rate of semi-major axis evolution is proportional to the mass ratio, binaries with large satellites (like Pluto-Charon, which is in DSS) tend to reach DSS more rapidly than binaries with small satellites (like the Earth-Moon system, which would take $\sim$50 Gyr to reach DSS).

Using the nominal values for Orcus and Vanth, the standard equation for semi-major axis evolution (MD99) can be integrated to show that for Orcus and Vanth, DSS is reached in about Q times 3 million years, similar to Pluto-Charon (Dobrovolskis et al. 1997). This speed is only slighly modified by using different tidal models. Eccentricity damping and obliquity decay are also very rapid, which can be shown analytically and which we have verified with direct simulations. In other words, if Vanth were formed in a collision, then for a reasonable set of tidal parameters, we would expect to see the system today in a circular orbit with the spin angular momenta aligned with the orbital angular momentum, and rotation rates equal to the orbital period of 9.58 days. If the Orcus-Vanth mass ratio is smaller than the nominal value, it can take much longer to reach DSS.

It is important to note that, if one or both of the binary components are spinning supersynchronously, tides can increase the eccentricity of the mutual binary orbit (e.g., Goldreich & Sari, 2009). Even collisional systems that started evolution with small semi-major axes could plausibly have large non-zero eccentricities due to tides. As tides continue to damp energy, however, the spins of the components slow and eventually reach a phase where tides reduce the eccentricity and the orbit will damp back to circularity. Since KBO systems may be in the intermediate regime, the observation of an eccentric orbit does not rule out formation by collision.

Is there observational evidence that Orcus and Vanth are in the double synchronous state? Unlike the Pluto-Charon system, the current configuration of Orcus and Vanth are such that the orbit pole is pointing nearly at Earth. If the rotation pole is aligned with the orbit pole, rotational photometric variability due to a variegated surface or aspherical shape would be negligibly small from our viewing angle. This is consistent with light curve measurements of Sheppard (2007) who find no variability in the light curve. Rabinowitz et al. (2007) report an unusually-shaped large-amplitude ($\Delta m \simeq 0.18$) light curve for Orcus, though their results may suffer from aliasing due to observing cadence of a long-duration observational campaign. Future more in-depth observations will be needed to clarify these results. If correct, the lack of photometric variability from Orcus is consistent with the expected pole-on orientation. Since the tidal timescale at the current separation is so short compared to the age of the solar system, it would require an unusual formation or tidal history to explain an Orcus-Vanth system that is not currently in the double synchronous state.

5.3 Tidal Evolution Inwards

Even if Orcus and Vanth are currently in the double synchronous state, this does not rule out tidal evolution from larger capture-like orbits. Since tidal evolution can shrink semi-major axes and damp eccentricities, it is possible that KBO binary orbits were wider and more eccentric in the past (GB08). Since an initial formation by capture (and subsequent dynamical friction) is inferred for other wide KBO binaries, it is not precluded in the case of Orcus and Vanth. However, a consideration of how these initial conditions were obtained is beyond the scope of this paper. In particular, the orbital and tidal evolution of KBO binaries while they are still in the dense planetesimal disk is not addressed. Our initial conditions start after the end of dynamical friction when the KBO binary has obtained its current heliocentric orbit, billions of years ago.

Under the capture formation model (e.g., Goldreich et al., 2002; Astakhov et al., 2005; Lee et al., 2007; Schlichting & Sari, 2008a), Orcus and Vanth would have originally been on independent heliocentric orbits in the primordial planetesimal disk. Upon entering one another's Hill sphere, either dynamical friction due to small bodies or the passage of another large body removes enough energy to permanently bind the two objects together. Subsequent dynamical friction can continue to remove energy from the binary, significantly shrinking the semi-major axis from $a \sim R_H \simeq 4000R_p$, the minimum Hill radius of Orcus-Vanth, to $a \simeq 18R_p$ seen today. As the orbital evolution of binaries during the dynamical friction phase has not been studied in detail, a wide variety of final configurations are theoretically plausible. These will correspond to the initial conditions before tidal evolution. In particular, we will consider initial conditions that resemble known KBO binary orbits: semi-major axes of several tens of primary radii and a wide range of eccentricities and inclinations (Noll et al., 2008a; Grundy et al., 2009).

There are a few general conclusions that can be drawn about the past orbital history of KBO binaries by making the reasonable assumption that tides conserve total angular momentum and that other processes acting on KBOs are not important for the angular momentum budget. (Including the effect of the Sun can lead to a non-conservation of angular momentum of the KBO binary and are discussed below; perturbations from passing KBOs may also be important.) Setting aside spin angular momentum, the orbital angular momentum of a binary is given by Equation 5.2 above. If orbital angular momentum is conserved, then $a(1-e^2) = a(1-e)(1+e)$ is conserved and the initial periapse distance $q_{\rm init} = a_{\rm init}(1-e_{\rm init})$ must be smaller than the current periapse as long as a has decreased. Including now the effect of spin angular momentum, we note that, although KBO spin periods are still not well characterized, formation arguments and observational evidence (Sheppard et al., 2008) support the idea that KBOs are not slow rotators compared to the typical binary orbit periods. So when a KBO binary forms, there is usually significant angular momentum in the spins of the components which can be transferred to the orbit over time through tidal torques. As long as these spins have some component in the prograde direction, the initial orbital angular momentum is smaller than seen today, which implies that the initial periapse distance must lie even closer than the case where spins are not considered. In other words, for an initial capture orbit to evolve into an orbit with smaller semi-major axis, the initial periapse must generally be closer than the current periapse and sometimes much closer, which we have also observed numerically in our model (described below). This limits the range of initial orbits that will evolve due to tides into the currently observed orbit.

5.4 Kozai Cycles with Tidal Friction

Based on the discussion above, if the initial orbit of Orcus and Vanth had a large semi-major axis typical of capture-like binaries (a/R_p of 50-100), this initial orbit should have had a periapse lower than the current periapse $q = 19R_p$. This implies quite large initial eccentricities, e.g., $0.6 \lesssim e \lesssim 0.9$. It is not clear whether the gravitational capture and subsequent dynamical friction or other perturbations can readily generate such large eccentricities and low periapses.

Secular perturbations due to the Sun can sometimes create large eccentricities and low periapses through Kozai oscillations (PN09). Kozai oscillations or Kozai cycles are large variations in eccentricity and inclination which can occur when the relative inclination between the heliocentric orbit and the binary mutual orbit, referred to as i throughout this paper, exceeds a critical value (typically $40° \lesssim i \lesssim 140°$) as originally pointed out by Kozai (1962) and Lidov (1962). These oscillations cause the eccentricity and inclination of the KBO binary to exchange on long timescales (set by the specific parameters of the system), while keeping $\sqrt{1-e^2}\cos i$ constant (Kozai, 1962).

It is useful to consider a coordinate system centered on the barycenter of the KBO binary orbit. In this system, the Sun's orbit about the binary is just the heliocentric orbit of the binary about the Sun. Averaging over the orbit of the Sun in the quadrupole approximation (higher order terms are very small for KBO binaries; Ford et al., 2000), the amplitude of Kozai oscillations depends on the initial relative inclination and binary KBO eccentricity, while the mass and distance of the third body perturber are only important in setting the Kozai oscillation timescale (Kiseleva et al., 1998):

$$\tau_{\rm Kozai} \simeq \frac{2}{3\pi}\frac{P_{\rm helio}^2}{P}(1-e_{\rm out}^2)^{3/2} \tag{5.3}$$

Including the effect of Kozai oscillations in the evolution of KBO binaries is important because many KBO binaries are subject to these oscillations (PN09) and *the high eccentricity phases of these oscillations can significantly lower the periapse distance, leading to strong tidal evolution of otherwise distant bodies.* This effect is known as Kozai Cycles with Tidal Friction (KCTF) and may be an important way of modifying KBO binaries, as it is for close stellar binaries and some hot Jupiter exoplanets (Mazeh & Shaham, 1979; Kiseleva et al., 1998; Fabrycky & Tremaine, 2007).

KCTF is an effective way of reducing orbital size and works in the following way. A wide KBO binary starts out with a periapse too high for significant tidal evolution, but at a significant relative inclination, i, to the binary's heliocentric orbit. Kozai oscillations due to the perturbations of the Sun cause an increase in eccentricity which can in many cases lead to quite small periapse distances during the maximum eccentricity phase. During the high eccentricity phases, tidal damping at periapse is significantly enhanced, which shrinks the orbit, but may not initially affect Kozai oscillations. This process continues until the periapse is low enough that apsidal precession due to other sources of apsidal precession are strong enough to suppress Kozai cycles (see below) and the orbit freezes near its high eccentricity state. Continued damping circularizes the orbit near the periapse position, leading to a circular orbit at a much smaller semi-major axis than the original orbit. KCTF can significantly lower the orbital periapse as it avoids the angular momentum argument described above: Kozai oscillations only conserve the z component of the binary's orbital angular momentum and smaller final orbits can be made by simply changing the initial inclination.

There are three requirements that KCTF must meet in order to significantly shrink a binary orbit. First, the initial relative inclination and eccentricity must fall in the regime where Kozai oscillations are significant: typically $40° \lesssim i \lesssim 140°$, though this range can be broadened somewhat in the presence of non-zero initial eccentricity. This is true of many KBO (and asteroid) binaries (PN09), including Orcus and Vanth, which currently have a relative inclination of $i \simeq 66°$. Second, the minimal periapse achieved by the Kozai cycle must be in a range where tidal forces (which depend on the radii, Love numbers, and tidal Q values) between the two objects are significant. Otherwise, the eccentricity and inclination simply oscillate without any long-term trend. There are probably many KBO binaries that fall in this regime and we note that even with tides are not important, KBO binary orbits can be significantly modified due to the Kozai effect.

Finally, additional minor perturbations to the orbital orientation must be small because Kozai cycles are caused by very slight perturbations that add coherently on secular timescales. In particular, the change in eccentricity due to the Kozai effect, $\dot{e} \propto \sin 2\omega$, can be averaged to zero if ω is precessing too quickly. Even in the presence of minor additional apsidal precession, the weak third-body perturbations are inefficient and Kozai cycles are suppressed. It can be shown analytically and numerically that if the periapse precession period due to other perturbations is shorter than the Kozai cycle timescale (Equation 5.3) by more than a factor of $\sim$2, the Kozai effect is significantly suppressed (Fabrycky & Tremaine, 2007). That is, in the presence of additional apsidal precession, the amplitude of eccentricity and inclination oscillations is quickly minimized, preventing KCTF. (Such suppression also significantly shortens the period, by as much as an order of magnitude, of any residual Kozai oscillations.)

Additional satellites are very effective at suppressing Kozai cycles (e.g., Innanen et al., 1997, but see Takeda et al., 2008), so KCTF cannot directly form the Haumea or Pluto multiple systems, though these are both in the Kozai inclination regime. For solid body binaries without additional satellites, the dominant source of apsidal precession is usually due to a permanent quadrupole moment (characterized by J_2) of the primary and/or secondary. We define this J_2 as the quadrupole due only to permanent asymmetry supported by the non-zero material strength of KBOs, i.e., it is the non-hydrostatic component of the gravitational quadrupole. The fluid quadrupole of tidal and rotational bulges is taken care of through additional terms, though we find that these quadrupoles are only important if the permanent asymmetry is extremely small (see Appendix). This work extends the preliminary analysis of PN09, who considered purely fluid bodies, by including precession due to J_2 and the resultant suppression of Kozai cycles.

Whatever the source of additional precession, the effect is to reduce the e and i amplitude of Kozai oscillations, potentially disabling KCTF. When $\dot{\omega}_{others}\tau_{\rm Kozai} \gg 1$, Kozai cycles are effectively turned off. When $\dot{\omega}_{others}\tau_{\rm Kozai} \ll 1$, then Kozai cycles are unimpeded and the amplitude is determined by only the initial eccentricity and inclination. Again, note that the mass and distance of the Sun do not effect the amplitude of Kozai cycles, but only the period of oscillation (approximately the same as τ_{Kozai}). When $\dot{\omega}_{Kozai}\tau_{\mathrm{Kozai}} \sim 1$, then the amplitude of Kozai cycles is attenuated. In this case, a full dynamical model (used below) is generally needed to determine whether KCTF can significantly shrink and circularize binary orbits.

Besides the importance of Kozai oscillations and KCTF, the perturbations of the Sun play another important role that affects the spin and orbital evolution of KBO binaries. Since the Sun induces additional apsidal and nodal precession of the KBO binary, including the Sun changes the equilibrium spin states of the system, generally known as Cassini states. For more information on Cassini states, see, e.g., Peale (1974) or Fabrycky et al. (2007). There are multiple equilibrium positions for each spin axis called Cassini states 1-4 which depend strongly on all sources of orbital precession. Tidal evolution will quickly bring the spin axes to one of these states (though state 3 is unstable to further tidal evolution). Unless the obliquity is $0°$, bodies in Cassini states still raise tidal bulges and the resulting orbital evolution modifies the location of the Cassini states themselves (Fabrycky et al., 2007). The obliquities of the bodies at any particular time, then, depend on the initial conditions and the amount of tidal evolution. In the absence of the Sun (but keeping precession due to J_2 and rotational and tidal bulges) and in the presence of significant tidal dissipation, the equilibrium obliquity between the spin axis and the binary mutual orbit axis will eventually end up in Cassini state 1 with a nearly zero obliquity (Fabrycky et al., 2007). In our integrations, we have found that including a highly-inclined Sun tends to drive the system into high-obliquity Cassini states, sometimes with very large obliquities (even greater than $90°$). Though these high-obliquity Cassini states are unstable on very long timescales, the rate of tidal evolution is strongly affected after capture into a Cassini state, and including the spin evolution of the bodies is important for capturing the correct evolution. Note that solar modifications of Cassini States can be important at any relative inclination, independently of Kozai oscillations. Though beyond the capability of current observations, precise measurements of the spin poles of KBO binary components could reveal non-zero Cassini obliquities, which would constitute an indirect measurement of the value of J_2.

5.5 Orbital Evolution Models

We have shown above that an orbital and tidal evolution model appropriate for KBO binaries require both validity at arbitrary eccentricity and the ability to include the effects of the Sun.

Let us now discuss specific tidal evolution models. The only attempt of which we are aware to investigate the tidal evolution of KBO binaries in high eccentricity orbits is that of GB08. These authors point out the important possibility of tidal evolution from a capture orbit for Dysnomia, the small moon of dwarf planet Eris (Brown & Schaller, 2007). Though our work supports their general conclusion, that tidal evolution inwards could create the tight circular orbit of Dysnomia, there are some serious flaws in the tidal model they employ (GB08 Equation 1). The tidal evolution equations used are taken from Jackson et al. (2008) (not including minor corrections mentioned by Jackson et al., 2009), who combined tidal evolution equations from Kaula (1968) and Goldreich & Soter (1966). One unincluded aspect of the original equations is the well-known change in sign of the tidal evolution depending on the whether the binary orbital period is sypersynchronous or subsynchronous with respect to the spin rate. The evolution of spin rates (and conservation of total angular momentum) is not considered at all. Finally and most importantly, the equations used neglect eccentricity terms of order e^4 and higher, as well as non-zero inclinations. At moderate eccentricities ($e \gtrsim 0.2$), these "higher-order" terms actually dominate the evolution because the coefficients of these terms are much larger than 1. For example, Wisdom (2008) finds that the energy dissipation rate (related to the eccentricity damping rate) is enhanced over the rate predicted by GB08 by a factor of 10^4 at $e \simeq 0.8$, the initial eccentricity estimated by GB08 for Eris and Dysnomia. The reason for this enhancement is to account for the fact that the strength of tidal interactions is a strong function of separation, e.g., r^{-6}. When computing the total torque averaged over one orbital revolution, $< r^{-6} >$, it is clear that interactions at periapse $q = a(1 - e)$ completely dominate the evolution, even when accounting for the fact that the satellite spends the least time near periapse. To adequately account for this physical phenomenon requires keeping higher order eccentricity terms; otherwise, substituting $a \approx r$ massively underestimates the strength of tides in highly elliptical orbits (e.g., Kaula, 1964; Mignard, 1980; Eggleton & Kiseleva-Eggleton, 2001; Wisdom, 2008).

GB08 justify the choice of low-eccentricity equations by correctly noting that tidal dissipation at large eccentricities is not well understood (some issues involved in high-e dissipation are discussed in Appendix A below). However, their model does not avoid this problem: it is simply a model in which all the eccentricity coefficients of order higher than 2 have coefficients equal to exactly zero, which does not capture the importance of tidal dissipation at periapse discussed above. Although these authors are correct in pointing out that tidal evolution from large semi-major axes can result in circular orbits, they actually underestimate significantly the tidal damping time.

We choose a different tidal evolution model to describe the orbital history. The equations of Eggleton & Kiseleva-Eggleton (2001, hereafter EKE) are used as the framework to model the full orbital and spin evolution of the binary system. The evolution equations are more fully described in Appendix A, with only the most relevant points explained here. The EKE model uses the equilibrium tide model to calculate the rate of tidal evolution and is valid at any mass ratio and eccentricity (though at the very highest eccentricities, when pericenter orbital frequency rivals solid body oscillation frequencies, a dynamical tide model may be more appropriate than the equilibrium tide model). Since the spin evolution is also tracked, the effects of non-zero obliquity, spin orientation, and spin rate are all accounted for, accurately including the appropriate direction of tidal evolution for subsynchronous, synchronous, and supersynchronous orbits.

These equations describe the secular evolution obtained after averaging over the orbital period, e.g., it does not contain any dependence on the orbital phase. Throughout the integration, the EKE equations describe the evolution of the apsidal and nodal precession of the orbit, the evolution of the semi-major axis and eccentricity, and the orientation of the spins of both bodies in inertial space. As presented, the EKE equations include the effects of the rotational and tidal bulges of both bodies, general relativity, perturbations from a distant third body (averaged over the orbit of that body to the quadrupole order), and tidal damping. Though the EKE equations were derived for stellar systems (hence the inclusion of general relativity), it can easily be extended to other binary systems as it makes no assumptions about the masses (or relative masses) of the three bodies. Integration of the EKE equations self-consistently accounts for Kozai oscillations, Cassini states, and tidal evolution, though there are some issues with the tidal evolution model used (see Appendix).

We have modified the EKE equations to be more appropriate for Kuiper belt binaries; see the Appendix for the full description of the model. We have added the effect of a gravitational quadrupole due to permanent asymmetry in a solid body, characterized in terms of an effective J_2. For the vast majority of KBOs, this additional J_2 term will dominate the rate of apsidal and nodal precession. Hence, the inclusion of J_2 is very effective at suppressing Kozai oscillations.

We have also restructured the tidal dissipation terms in terms of tidal dissipation parameter Q, as appropriate for solid bodies (Fabrycky et al., 2007). The EKE model also calculates perturbations to the binary orbit due to a distant third body and we have added the effect of the Sun on these binary orbits. The influence of the Sun can make major modifications to the orbital and tidal evolution of KBO binaries, as described above.

5.6 Application of KCTF Model to Orcus-Vanth

One of the most important, but unknown, properties of Orcus and Vanth is J_2. Since the current orbit is very nearly circular ($e < 0.003$ Brown et al., 2009), it is reasonable to assume that Kozai cycles are suppressed in the current system. We find that increasing apsidal precession by adding a permanent asymmetry of Orcus of $J_2 \simeq 4 \times 10^{-6}$ is sufficient to suppress Kozai cycles in the currently observed system. This J_2 corresponds to moving only a few meters of material from the pole to the equator of a perfectly spherical object; the actual value of J_2 is probably much higher. One source of permanent asymmetry may be a frozen-in rotational bulge from early formation that has not relaxed. We can estimate J_2 from such a bulge using $J_2 = k_2 q_r/3$ where $q_r = \nu^2 R^3/GM$, ν is the spin frequency, and k_2 here is the Love number of the body before the bulge freezes. The initial rotation rate was probably somewhat near breakup (2.9 hour spin period) where $q_r \approx 1$, easily yielding J_2 as high as $\sim$0.001 or higher. Unfortunately, there is no clear way to estimate the J_2 of KBOs, whose shapes are very poorly known. Again, we point out that our use of J_2 is to represent the non-hydrostatic quadrupole moment due solely to the permanent asymmetry; this is not necessarily the J_2 that would be measured astrometrically by observing apsidal precession in the system unless the permanent asymmetry is the dominant source of quadrupolar precession (which is likely; see Appendix A).

Using our model, we have performed several integrations with a wide variety of initial conditions and subsequent evolutions. This exploration was performed with two goals: 1) to gain a general understanding of the variety of orbital evolution regimes possible and 2) to approximately reproduce the Orcus-Vanth system (circular orbit with $a \approx 9000$ km and $i \approx 66°$) from a much wider initial orbit through KCTF.

To describe the evolution of various systems, it will be useful to define a few quantities: $q_{\rm Kozai}$, a_{J_2}, $q_{\rm min}$ and $q_{\rm tides}$. For a particular KBO binary the true values of these quantities depends on a variety of unknown factors and can only be estimated.

If the initial eccentricity is zero, then the minimum periapse achievable is $q_{\rm Kozai} = a(1 - \sqrt{1 - \frac{5}{3}\cos^2 i_{\rm init}})$, where $i_{\rm init}$ is the initial inclination; for $i_{\rm init}$ near 90°, the minimum unsuppressed periapse can be made arbitrarily small.

Significant suppression of Kozai oscillations occurs when $\dot{\omega}_{J_2}\tau_{\rm Kozai} \simeq 2$, evaluated at $e = 0$, which we have verified numerically and matches the result of Fabrycky & Tremaine (2007). Using Equations 5.7 and 5.3 we can estimate the semi-major axis at which point Kozai suppression would begin, a_{J_2}, assuming that J_2 is the dominant sourceof precession:

$$a_{J_2} \approx (J_2 R^2 R_H^3 (1 - e_{\rm helio}^2)^{3/2})^{1/5} \tag{5.4}$$

where $R_H \equiv \left(\frac{m_1+m_2}{3M_{Sun}}\right)^{1/3} a_{\rm helio}$ is the Hill radius of the binary. For example, in the Orcus-Vanth system with $J_2 \simeq 0.001$, this yields $a_{J_2} \approx 43R_p$. When $a \simeq a_{J_2}$, Kozai cycles are suppressed, and the actual minimum periapse achieved may by higher than $q_{\rm Kozai}$. Call the actual minimum periapse achieved in suppressed Kozai cycles $q_{\rm min}$, which depends mostly on the initial semi-major axis, inclination, and J_2. Finally, let $q_{rmtides}$ be the periapse distance where tidal effects can significantly affect the KBO binary. This will depend mostly on the unknown tidal parameters k_2 and Q.

The values of $q_{\rm min}$ and $q_{\rm tides}$, along with the initial spin angular momenta of the binary components, are generally the most important parameters in determining the final outcome of orbital evolution. For example, the initial eccentricity, argument of periapse, or longitude of ascending node of the KBO binary do not significantly modify the final orbit achieved. The relative values of $q_{\rm min}$ and $q_{\rm tides}$ can be used to qualitatively describe the early evolution until Kozai cycles are suppressed and further evolution is determined mostly by conservation of angular momentum.

If $q_{\rm tides}$ is much closer than $q_{\rm min}$, then tides are not strong enough to affect the binary orbit and Kozai cycles proceed unimpeded. This can occur when Q is high (weak tidal dissipation) or J_2 is high (efficient Kozai suppression).

If, on the other hand, $q_{\rm tides}$ is much higher than $q_{\rm min}$, then during the course of the first Kozai cycle, the periapse reaches the regime where tides are important. These tides can shrink the periapse and quickly bring the semi-major axis below a_{J_2}, turning off Kozai cycles. When tides are not as strong, they can slowly shrink the orbit over several Kozai cycles, eventually reaching a regime where the semi-major axis has been lowered enough to suppress Kozai cycling ($a \lesssim a_{J_2}$). Once the Kozai effect is inactive, tidal evolution occurs according to conservation of angular momentum. As discussed above, damping the eccentricity then leads to an overall increase in periapse. Furthermore, during Kozai cycles, the spin rates and directions of the two bodies are not strongly affected. So the initial spin angular momentum, now efficiently coupled to the orbit through tides, also acts to increase the semi-major axis and periapse, as long as the spins are somewhat prograde.

It is interesting to note that the final semi-major axis achieved with KCTF is about the same as the final semi-major axis achieved with tidal evolution outwards from the Roche lobe: in both cases, the final position is located at a distance where tidal effects are important $\sim q_{\rm tides}$. For the same reason, when tidal evolution at the current position of Vanth is relatively strong, both tidal evolution outwards and tidal evolution inwards have sufficient time in the age of the solar system to produce the binary properties seen today.

When KCTF was active in our integrations, we found a wide variety of possible final semi-major axes, $3R_p \lesssim a \lesssim 30R_p$, with a preference for lower values. One example of a system that, through Kozai Cycles with Tidal Friction, shrinks significantly in semi-major axis is shown in Figure 5.1. Unlike in the case of collisions, tidal evolution inwards from a capture orbit does not produce a binary with a specific value of J. That the observed value of J matches well to the value expected from collision models would be essentially a coincidence if the system tidally evolved inward from a capture-like orbit.

The final inclination of the binary is essentially frozen in when the periapse is low enough that Kozai cycles become completely suppressed. This often happens when the eccentricity is maximized, which most often occurs when the inclination is near the critical angle, i.e., $i \approx 40°$ or $140°$ (Fabrycky & Tremaine, 2007). This is the case in the integration shown in Figure 5.1. Higher inclinations can occur when the oscillation amplitudes are suppressed, the initial eccentricities are high, or if tides are particularly strong (when $q_{\rm tides} \gg q_{\rm min}$) so that Kozai cycles can be broken before the maximal eccentricity is reached. Note that, when including the aspects of spin evolution, it is possible to have final inclinations outside the Kozai range and it is also possible for prograde orbits to "roll over" and become retrograde orbits. This ability of Kozai cycles to significantly change the inclination distribution of KBO binaries will unfortunately make it difficult to identify the primordial inclination distribution predicted by Schlichting & Sari (2008b).

Our simluations are able to produce Orcus-Vanth binaries in circular orbits with a range of semi-

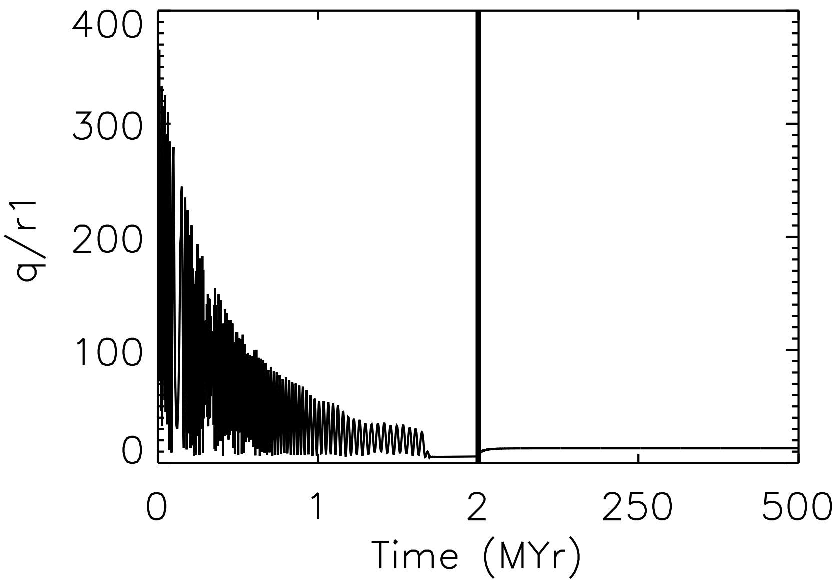

Figure 5.1 **Evolution of the Peripase of a KBO Binary undergoing KCTF.** We used our model for the orbital and tidal evolution of KBO binaries to explore a variety of initial conditions, in order to attempt to reproduce the Orcus-Vanth binary. The time evolution of the periapse ($q = a(1-e)$, q/R_p is shown) for one of our integrations is shown above. Note the difference in the time axis between the left and right side of the graph. In this integration, the physical properties of the binary components matched that of Orcus and Vanth, including a J_2 of 0.0004 and 0.005 respectively. The initial semi-major axis, eccentricity, and inclination were 950 R_p, 0.6, and 82.7° respectively, so that the initial orbital periapse would have been 380 R_p or nearly 200000 km. At this separation, tidal evolution is completely negligible. However, because the initial inclination is in the Kozai regime, Kozai cycles significantly modify the eccentricity, allowing the system to reach very low periapse values. These Kozai oscillations are initially very rapid and slow as the orbital period shrinks due to tidal evolution, which is effective when the periapse reaches $\sim$20 R_p. Aided by a reduction in periapse due to the Kozai cycles, the orbit shrinks significanly, reaching $a \simeq 100R_p$ within 1.7 MYr. At this point, additional precession from J_2 is able to suppress Kozai cycles and the orbit stabilizes, as always, with a high eccentricity and low periapse. In this case, the final inclination is about 34°; it is typical that Kozai cycles will cease at the highest value of eccentricity, corresponding to the lowest value of inclination (which is usually near the critical inclinaiton of $\sim$40°). Further evolution is dominated by tidal dissipation, which raises the periapse due to conservation of angular momentum (Equation 5.2) until the orbit becomes nearly circular after about 50 MYr. The spins of both components are in Cassini states and the Cassini obliquity damps to nearly zero on the same timescale. The final system looks similar to the Orcus-Vanth binary today, except for the lower mutual inclination (34° instead of 66°). Further exploration of parameter space indicates that reasonable variations in initial conditions could easily increase the final inclination of the simulated Orcus-Vanth to match the observed inclination.

major axes and inclinations that span the observed values. Since the orbital evolution is somewhat chaotic and the parameter space of initial conditions is very large, we have not identified a specific model that reproduces the currently observed system. However, the results we do find give no indication that it would be difficult or impossible to produce this system from capture-like initial conditions during the age of the solar system.

During the tidal dissipation phase of evolution, we have found that the spin state of the primary and/or secondary will typically go to an equilibrium Cassini State. Most tidally-affected bodies in the solar system are in the low-obliquity Cassini state 1, with the notable exception of the Earth's Moon which is in Cassini state 2. Cassini state 2 is usually available either when the obliquity starts relatively high and/or perturbations from the Sun are relatively strong at large semi-major axes. Many of our integrations put the bodies, especially the primary, in Cassini state 2. This is especially true when J_2 is relatively high. As the eccentricity damps to nearly zero and the semi-major axis shrinks at the expense of spin angular momentum, the primary (or secondary) can sometimes maintain the large Cassini state 2 obliquity for long times. In some cases, there is a phase of KCTF evolution where the orbit is nearly circular, but the angle between the spin of Orcus and the binary orbital angular momentum is still substantial. This is an important observational consequence of KCTF, as Cassini state 2 is not likely to be reached by systems that form in a collision and tidally evolve outward. The converse is not true; that is, if a KBO binary is found to have low obliquity (as may be the case for Orcus) it does not imply that KCTF was not active, e.g., tides may have been sufficiently strong to force the transition into Cassini state 1 (Fabrycky et al., 2007).

5.7 Discussion: General effects of KCTF on KBO binaries

Besides the Orcus-Vanth system, we have also applied our model to the Eris-Dysnomia system, which also has a relative inclination in the Kozai regime: $i \simeq 78°$ or $i \simeq 102°$ in the two possible orbit solutions (Brown & Schaller, 2007). We did not explore this system in detail, but reach the same conclusion as GB08: theoretically, Eris and Dysnomia could have started on a much wider, more eccentric orbit and through Kozai cycles and tidal friction, ended in the orbital orientation seen today. The large heliocentric inclination of Eris ($i_{\text{helio}} = 44.2°$) was presumably created in an early scattering event and illustrates the possibility that changes in the heliocentric orbit of the KBO binary could potentially affect whether the relative inclination (which depends on both the heliocentric inclination and the binary orbit pole direction) is susceptible to Kozai oscillations.

With the current information, it appears that the Orcus-Vanth and Eris-Dysnomia binaries could have formed through either collision or capture. In the future, with more binaries and better observations, the observational signatures of KCTF will be more testable. These signatures include the following (see also PN09).

- Binaries whose orbits are indicative of KCTF evolution.
- Close binaries on nearly circular orbits with substantial obliquities.
- An underabundance of KBO binaries with relatively large periods and nearly perpendicular inclinations along with an overabundance of short-period binaries with inclinations near the critical Kozai inclination (e.g., Figure 8 of Fabrycky & Tremaine 2007).

We caution that there are significant observational biases present in the current distribution of KBO binaries in that all relative inclinations are not sampled evenly. For example, systems that have low relative inclinations always present nearly edge-on orbits with respect to Earth-based observations, while systems with high relative inclinations are usually face-on as seen from Earth. Since KBO binaries are discovered when the components are significantly separated ($\gtrsim 0.2$ arcseconds) during a single Hubble observation, there is a greater likelihood for edge-on secondaries to be unresolvable when observed at a single random epoch, especially for binary separations near the limiting resolution.

On the other hand, for some specific KBO systems, it will be possible to rule out KCTF as an important source of orbit modification. This is most easily done with the observation of an additional satellite, both because these satellites suppress Kozai oscillations and also because they limit the orbital evolution possible under the reasonable assumption that satellite orbits never crossed in the past. This rules out the evolution of satellites of Pluto and Haumea by KCTF alone (but see the "orbital collision" model below). The presence of an extant collisional family like the Haumea family (Brown et al., 2007) would be another clear sign that the binary was formed by a collision that occurred after the Kuiper belt attained its current structure. Finally, with long-term astrometric observations of some binary systems, a direct detection or upper limit of J_2 can provide insight into the likelihood of past evolution due to KCTF.

Tidal dissipation (inwards or outwards) of the orbital and rotational energy of KBO binaries only produce minor temperature enhancements; for the Orcus-Vanth binary, the average temperature increase due to orbital energy is less than 1 Kelvin while the average temperature increase due to spin energy could have been as high as 10 Kelvin. Smaller KBOs will dissipate even less energy. Since this energy is deposited over very long timescales, tidal dissipation generally has little effect of the thermal properties of KBOs and binaries that evolved inwards or outwards will not have identifiable surface features due to tidal heating. On the other hand, giant impacts can strongly affect the interior and surface states of these systems, though the unique observable consequences of such collisions is unclear.

We hypothesize that a hybrid scheme of KCTF-induced collisions may be possible and important for forming KBO binaries. In this case, KCTF increases the eccentricity and drops the periapse to very low values, as long as Kozai cycles are not suppressed (e.g., $a \gtrsim a_{J_2}$). Even for very low J_2 values, this generally occurs at periapses above the Roche limit, unless a is very large (hundreds of primary radii). In these very high eccentricity phases, it may be possible for the orbit to evolve to an unstably low periapse. This may be assisted by small non-tidal perturbations, e.g., passing or impacting KBOs, which could lower the periapse beyond that achieved by Kozai cycles alone. Once the periapse descends into the Roche lobe, an equilibrium tidal model fails, but it seems unlikely that continued interactions between objects on highly elongated orbits with very low periapses will be able to avoid eventual collision. Unlike a collision between two unbound objects, the relative velocity of the bodies in such an "orbital collision" is lower than the escape velocity from the primary by a factor of about $\sqrt{\frac{1+e}{2}}$. Such a grazing weak collision can still result in a disk from which new satellites would coalesce; these satellites may then evolve outwards due to tides.

It is interesting to note that such a formation mechanism is apparently consistent with the successful simulations of Canup (2005), which explored the giant impact that produced the Pluto-Charon system using a Smoothed Particle Hydrodynamics method. Canup (2005) found an entire suite of simulations between equal size objects on trajectories with $v_{imp} = v_{esc}$ and nearly grazing impact parameters ($0.83 < b < 0.96$) that successfully produced disks or intact moons with the angular momentum and mass ratio that would evolve into the current Pluto-Charon system. These are similar to the impact parameters that would result from a decaying highly eccentric orbit. It is interesting to note that the prevalence of KBO capture binaries of nearly equal masses, coupled with the likelihood of Kozai cycles at high relative inclinations may imply that such orbital collisions are not uncommon. Furthermore, this method naturally produces impact velocities near the mutual escape velocity, regardless of the surrounding dynamical environment. (The orbital collision model is not favored for binaries where the inferred impact velocity is significantly larger than the escape velocity.)

The opposite effect is also possible: KCTF can unbind KBO binaries if the system properties are right. When the initial inclination of a binary is near 90°, the maximal eccentricity reached due to Kozai oscillations can be very high. Goldreich (1963) pointed out that tidal effects on very high eccentricity orbits are likely to increase both the semi-major axis and the eccentricity. In our integrations, we found that KCTF can occasionally lead to orbits that quickly increase in semi-major axis and eccentricity, gaining angular momentum from the spins of the component until the binary disassociates. This is the tidally-evolved extension of the "Kozai-Hill" instability mechanism of PN09, who note that high eccentricity phases of Kozai oscillations can lead to orbital apoapse distances exceeding the Hill radius.

5.8 Conclusions

There is strong circumstantial evidence that Orcus's satellite Vanth formed in giant collision. Here we have proposed an alternative explanation for the current orbital state: starting on a wider capture-like orbit, Kozai perturbations due to the Sun cause the eccentricity (and inclination) to oscillate with large amplitudes, occasionally bringing the periapse low enough to be affected by tidal evolution. This process continues until tidal dissipation brings the periapse low enough to suppress Kozai oscillations, after which the orbit circularizes and the spin angular momenta of Orcus and Vanth are converted to orbital angular momentum. Similar processes may be important for a wide variety of KBO binaries. Kozai Cycles with Tidal Friction (KCTF) may significantly modify KBO binary orbits from their initial distribution.

Though it is difficult to prove or exclude the possibility of KCTF for single systems, the ensemble of KBO binaries may contain the signatures of KCTF evolution, e.g., a lack of wide binaries at relative inclinations near $i = 90°$. More observational and theoretical study of both individual KBO binaries and the entire population will be able to elucidate the importance of KCTF for creating the currently observed distribution. Many of the conclusions we have drawn for KBO binaries are also applicable to asteroid binaries (PN09).

Tidal and orbital evolution can clearly make significant modifications to the primordial binary orbit distribution. Understanding the effect of Kozai oscillations and tidal dissipation on the currently observed properties of KBO binaries will help debias the interpretation of the origins of KBO binaries. In particular, the observation of a short-period circular orbit for Orcus and Vanth can not be immediately attributed to a purely collisional origin.

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5.9 Appendix: The Orbital Evolution Model

5.9.1 Introduction to EKE Framework

We use the orbital and tidal evolution framework of (Eggleton & Kiseleva-Eggleton, 2001, hereafter EKE), which was originally developed for stellar systems, but with the minor adaptations described below, can be applied to solid body binaries. For more information on this framework, see Eggleton et al. (1998); Mardling & Lin (2002); Fabrycky & Tremaine (2007); Fabrycky et al. (2007). The original unmodified integration code was kindly provided by D. Fabrycky.

The EKE equations describe the evolution of 4 vectors: $\vec{e}$, $\vec{h}$, $\vec{\Omega}_1$, and $\vec{\Omega}_2$, which represent the Laplace-Runge-Lenz eccentricity vector, the orbital angular momentum vector, and the spin vectors of both bodies, respectively. The magnitude of $\vec{e}$ is the eccentricity, e, and the direction points in the direction of periapse. The evolution of semi-major axis is evaluated indirectly through $h = \sqrt{G(M_1 + M_2)a(1 - e^2)}$. These coordinate system used to describe these vectors is the orbital orientation of the outer binary, called ($\vec{E}$,$\vec{Q}$,$\vec{H}$) in EKE, where $\vec{Q}$ is a vector perpendicular to the eccentricity vector for the outer binary, which is needed to form a perpendicular right-handed triad of unit vectors. In the original EKE formalism, ($\vec{E}$,$\vec{Q}$,$\vec{H}$) is not necessarily an inertial reference frame, but since we assume that the heliocentric orbit is fixed (and is not significantly changed by interactions in the KBO binary), this is an appropriate approximation (Fabrycky & Tremaine, 2007).[1] Note that the quantities we are interested in are independent of the reference frame. The EKE equations describe the force and torque couples needed to evolve the 12 components of $\vec{e}$, $\vec{h}$, $\vec{\Omega}_1$, and $\vec{\Omega}_2$. As our implementation of the integration uses a variable timestep and automatically stops when the system reaches the double synchronous state (DSS), the time needed to integrate for the age of the solar system varies from a few seconds to days, depending on the initial conditions and parameters of the integration.

There are two modifications made to the EKE equations that are needed to adapt the system for solid bodies. The first is an addition of apsidal and nodal precession terms due to the quadrupole moment of any permanent asymmetry, J_2. For small solid bodies, material strength can support permanent mass anomalies and significantly non-spherical shapes. The second is writing the tidal dissipation in terms of Q.

5.9.2 Adding Permanent Asymmetries

Expanding a J_2 potential (Murray & Dermott, 2000) and using the notation of EKE, we find

$$X_{J_{2,1}} = \frac{3}{2} J_{2,1} \left(\frac{R_1}{a}\right)^2 \frac{n}{(1-e^2)^2} \frac{\Omega_{1h}\Omega_{1e}}{\Omega_1^2} \tag{5.5}$$

$$Y_{J_{2,1}} = \frac{3}{2} J_{2,1} \left(\frac{R_1}{a}\right)^2 \frac{n}{(1-e^2)^2} \frac{\Omega_{1h}\Omega_{1q}}{\Omega_1^2} \tag{5.6}$$

$$Z_{J_{2,1}} = \frac{3}{4} J_{2,1} \left(\frac{R_1}{a}\right)^2 \frac{n}{(1-e^2)^2} \frac{2\Omega_{1h}^2 - \Omega_{1e}^2 - \Omega_{1q}^2}{\Omega_1^2} \tag{5.7}$$

where $\Omega^2 = |\vec{\Omega}|^2$ and Ω_{1i} is the projection of the spin vector onto axis i, as in EKE; the spin-related terms are used to correctly account for the case of non-zero obliquity. These terms are added to the X_1, Y_1, and Z_1 terms of EKE and this procedure is repeated for body 2, which may itself have a J_2 large enough to dominate the precession of the system. In the appropriate limits, these equations

[1] We note here that some heliocentric orbits are not fixed in time due to the effects of other planets. In our model, the effects of other planets and passing KBOs are all ignored.

reproduce the expected J_2 evolution. In the set up of the EKE equations, these terms are used to calculate both the torque on the orbit due to the quadrupole and the corresponding back-torque of the orbit onto the quadrupole. Note that this J_2 is due solely to the permanent asymmetry supported by the material strength of these small solid bodies and that the effective J_2 of the tidal and rotational bulges is already accounted for through other terms.

Our proscription for including J_2 assumes that any permanent mass anomalies can be well-approximated by a degree-2 gravity field with an axis aligned with the rotational axis of the body[2]. This is true for rapidly spinning solid bodies, in which case J_2 is an effective time-averaged J_2, which for a tri-axial body has a value of $J_2R^2 = 0.1(\alpha^2 + \beta^2 - 2\gamma^2)$, where α, β, and γ are the semi-radii of the ellipsoid (Scheeres, 1994; Ragozzine & Brown, 2009). When the spin frequency and orbital angular frequency at periapse become comparable, or near higher-order spin-orbit resonances, this approximation begins to break down. Near synchroneity other unmodeled sources of tidal dissipation can become important, though their effect is to change slightly the time needed to achieve DSS (Dobrovolskis et al., 1997).

In the case of high-order spin-orbit resonances, tidal evolution can quickly break these resonances and ignoring them in our evolution should have no significant effect, especially if the final outcome is a circular orbit. We note that many KBO binaries have eccentric orbits: if tides are effective at slowing the spins of these bodies, they may be in high-order spin-orbit resonances. Recall that the purpose of including J_2 in the evolution is to provide a realistic source of natural apsidal precession that can suppress Kozai oscillations; after Kozai effects turn off early in the integration, J_2 has no significant impact on the remaining evolution, as it merely precesses the orientation of the orbit and spin poles. This has no long-term effect on tidal evolution rates outside of resonance.

We can compare the importance of a permanent asymmetry (J_2) and the next largest source of apsidal precession in highly eccentric orbits, which is usually precession due to instantaneous tidal bulges. If the rotation rate is significantly higher than the orbital period, the rotational bulges can be more important, depending on the eccentricity. The Z terms of the EKE framework describe apsidal precession, so we can compare $Z_{J_{2,1}}$ to the precession rate due to the instantaneous tidal bulge of body 1 (EKE):

$$\dot{\omega}_t = \frac{15}{2} k_2 \left(\frac{R_1}{a}\right)^5 n \frac{m_2}{m_1} \frac{(1 + \frac{3}{2}e^2 + \frac{1}{8}e^4)}{(1-e^2)^5} \tag{5.8}$$

Considering only body 1 and assuming zero obliquity, it can be shown that these two will be comparable when

$$J_2 \simeq 5k_2 \left(\frac{R_1}{q}\right)^3 \frac{m_2}{m_1} \tag{5.9}$$

where q is the periapse and where we have dropped the term $\frac{(1+\frac{3}{2}e^2+\frac{1}{8}e^4}{(1+e)^3}$, which is nearly equal to 1 for all eccentricities. Because of the stronger dependence of apsidal precession (of both tidal

[2]Even small KBOs ($r \gtrsim 1$ km) are expected to rapidly reach principal axis rotation

and rotational bulges) on the distance $\frac{R_1}{a}$, they are only dominant when the periapse is very low. Note that J_2 and k_2 can easily be of similar magnitude, even when the body is large enough to become spherical through hydrostatic equilibrium. In this case J_2 precession will dominate unless the periapse is within the Roche lobe at ~2.5 primary radii. For stable orbits, J_2 precession will be the dominant source of apsidal precession unless the solid body has very little permanent asymmetry and k_2 is rather large, though recall that significant enhancements to k_2 are possible for small rubble piles (Goldreich & Sari, 2009). Since Kozai oscillations significantly change the orbital orientation, this dominance is robust even when the angle between the spin and binary orbital axis is non-zero (and J_2 precession is reduced). By conducting a large range of short-term integrations of the EKE model, we have confirmed that systems where $J_2 = 0$ can reach minimal periapses of $q_{\rm min}$ within the Roche lobe. Including even a tiny permanent asymmetry ($J_2 \simeq 10^{-7}$), suppresses Kozai oscillations and raises the maximal periapse to outside the Roche lobe. Small bodies ($R \lesssim 200$ km), including most KBOs and all but the largest asteroids have sufficient material strength to defy hydrostatic equilibrium, resulting in very large J_2 values of order ~0.1. We also confirm directly that adding J_2 never lowers the minimum periapse and always acts to suppress the eccentricity and inclination amplitude of Kozai oscillations, while often increasing the oscillation frequency to ~10 times faster than the timescale given in Equation 5.3.

5.9.3 Tidal Q

The other modification appropriate for solid bodies is a change in the way solid body tides are treated. The original EKE formalism uses frictional timescales that can be expressed as a function of the viscous timescale of fluid stars. We modify the tidal friction timescale calculations in a way similar to Fabrycky et al. 2007:

$$\frac{1}{t_{F1}} = \frac{3n}{2}\frac{k_{2,1}}{Q_1}\left(\frac{R_1}{a}\right)^5 \frac{M_2}{M_1} \tag{5.10}$$

and similar equations for body 2 (which has the mass factor $\frac{M_1}{M_2}$). Tidal torques are proportional to t_F^{-1}.

The EKE model of tides assumes that the time lag of all tidal components are equal and constant in time. As discussed in Efroimsky & Lainey (2007), this corresponds to a frequency dependent Q with $Q \propto \chi^\alpha$, where χ is the tidal frequency (e.g., $2|\sqrt{\Omega_1^2} - n|$ for the diurnal tide) and where $\alpha = -1$ corresponds to the frequency dependence assumed by EKE. This same frequency dependence is also used in the model of Mignard (1980) and others. A wide variety of geophysical data for the Earth give $\alpha \simeq 0.3 \pm 0.1$ (Efroimsky & Lainey, 2007) and it is thought that a similar value would be relevant for icy bodies (Michael Efroimsky, personal communication, 2009). Hence, the negative frequency-dependence of Q assumed in the EKE model is unlike the geophysically-motivated positive frequency-dependence of Efroimsky & Lainey (2007) and also unlike the constant Q model of Goldreich & Soter

(1966) on which GB08 is modeled. Different frequency dependences of the component tides is the explanation for differing coefficients in the tidal evolution equations. Note that significant changes in the rotational and orbital frequencies under KCTF can be quite large, so that the value of α is important for determining the exact evolution. We experimented with incorporating a variable frequency dependence ($Q \propto \chi^{\alpha}$) and found that the main change was usually in the timescale of orbital evolution; as noted in the text, once the system breaks out of the Kozai resonance, the final parameters of the double synchronous state are determined solely by conservation of angular momentum.

Despite possible issues with Q, the EKE model accounts for the fact that, at high eccentricity, significant tidal damping at periapse enhances the tidal evolution rate over the above (which depends on a). Since the tidal torque is proportional to r^{-6}, the majority of tidal interactions occur near periapse (even when accounting for the fast that the orbit spends the least time near periapse). Using the EKE expansions derived for arbitrary eccentricity and obliquity significantly improves the accuracy of evolution over GB08 who use the low-eccentricity approximations of these equations in a regime where they are not valid.

5.9.4 Potential Improvements to the Model

To more accurately track tidal histories, the Kaula (1964) method of expanding the tidal potential into individual Fourier components would be superior. Then, each tide can be assigned the appropriate frequency dependence and the sign of the torque of each individual tidal component can be correctly accounted for. The Kaula (1964) expansion of tidal friction, with corrections and improvements from Efroimsky & Williams (2008), could be readily incorporated in the EKE framework, which would avoids some of the problems relating to tracking the correct inclination reference frame. To do this properly would involve one less averaging than taken in Kaula (1964), to account for the effect of the Kozai resonance on the argument of periapse, as pointed out in Efroimsky & Williams (2008).

Even this improved model would suffer from the difficulties encountered in all averaged models: they can not correctly handle resonances involving unresolved frequencies. For example, since our model averages over the orbital motion of the Sun, our model ignores the potentially important contribution of the evection resonance, when the orbital precession frequency is resonant with the heliocentric orbital period (Touma & Wisdom, 1998). Passage through this resonance can excite the system and this excitation is not included in our integrations. We do check the apsidal and nodal precession periods throughout our integration and find that these timescales are generally much longer than the heliocentric orbital period when the satellite is tidally evolving inwards. It can be shown that for a nearly-circular orbit, the evection resonance occurs at a semi-major axis of

$$a_{in} \simeq \left(\frac{27}{4} (J_2 R^2)^2 R_H^3 \right)^{1/7} \tag{5.11}$$

which is about 10 primary radii for the Orcus system, assuming $J_2 \simeq 0.005$. Unless J_2 is much higher, the 1:1 evection resonance is probably not important for tidal evolution inward from a larger orbit.

By far the largest drawback to our tidal model, which would only be partly remedied by using a full Fourier expansion of the tidal potential, is that the physics of tidal dissipation is not fully understood. Although most popular, tidal models that use Q implicitly assume that the bodies respond linearly to perturbations; once tidal stresses significantly exceed the yield stress of the body or if tidal components at different frequencies interact non-linearly, a hydrodynamical model should be used to calculate tidal perturbations. It may be true that the end result of such a model may be approximated by an "effective" Q value with a certain frequency dependence. Very close passes, significant lateral heterogeneity in the binary components, feedback between energy dissipation and tidal parameters, or other non-linear effects are also likely important in reconstructing precise tidal histories. Even in the Earth-Moon system, there is insufficient observational and theoretical data to fully reconstruct the orbital history of the binary system. Despite these drawbacks, we believe that the inclusion of a better tidal model would not change the general result that KCTF can be important for the orbital evolution of KBO binaries. Furthermore, investigations of the orbits of KBO binaries will only provide more constraints and insights into the relevant tidal physics; future analyses may be able to identify and accurately model the most important aspects of the tidal evolution of these systems.

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