High Fidelity Modelling of Contact Binary Asteroid Fission A. B. Davis[1] and D. J. Scheeres[1], [1] Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80309-431 (alex.b.davis@colorado.edu)

Introduction: The YORP induced fission and evolution of contact binary asteroids has been studied to explain the populations of tidally-locked binaries, asteroid pairs and other binary populations. Work by Scheeres studied the energetics of these systems and mapped their evolutionary pathways given simplified mas distributions [1]. Later work by Jacobson and Scheeres was able to numerically model these pathways and show statistical agreement with current observations of the Near-Earth Asteroid population. Their analysis also suggested a secondary fission process which could more efficiently dissipate energy in recently formed binaries [2]. Both of these studies were limited by an assumption of planar dynamics and second-order gravity models. By leveraging recent advancements in full two-body problem (F2BP) modeling we are able to lift these assumptions and explore their impact on the fission process. Most significant of these consequences is the apparent breakdown of the unstable inner equilibrium as a dynamical boundary to re-impact. In this work we attempt to identify modified dynamical and energetic boundaries in the fission and evolution of contact binaries.

Dynamics Model: When modelling the mutual dynamics of the asteroids we track the relative position and orientations of the bodies. Fig. 1 illustrates the geometry of the 9 degree of freedom system. To perform this analysis, we model the mutual gravity potential of the asteroids truncated at the fourth degree and order.

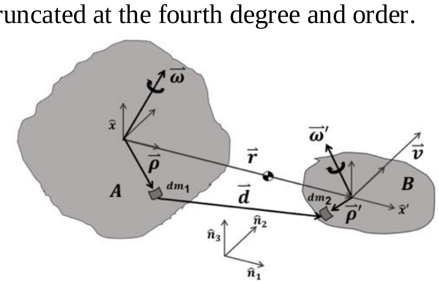

Figure 1: System diagram for the relative F2BP, where $\vec{\boldsymbol{r}}$ and $\vec{\boldsymbol{v}}$ are the relative position and velocity of the system and $\vec{\boldsymbol{\omega}}$ and $\vec{\boldsymbol{\omega}}'$ are the angular velocities of each body.

The mutual gravity potential model leverages inertia integrals of arbitrary order for simulation of arbitrarily shaped constant density bodies [3]. Inertia integrals, described in Eq. 1, are analogous to moments and products of inertia, but are computed for a series of expansion orders to describe more complex mass distributions, much like spherical harmonics.

$$T_B^{ijk} = \frac{1}{M_B r^{i+j+k}} \int x^i y^j z^k \, dm \; [\mathbf{1}]$$

In addition to the mutual gravitational acceleration the dynamics are perturbed by a Hill solar gravity model for a circular orbit and tidal torques. The force models for these perturbations are adapted from the planar formulations in Murray and Dermott [4].

Fission Process: Traditionally, when studying contact binary fission, the fission event is defined by the unstable relative equilibrium of the F2BP. Analysis of the energetics about this equilibrium show that it acts as a dynamical boundary between collision of the asteroids and a bounded mutual orbit. These boundaries are illustrated in Fig. 2 by holding the angular momentum constant and evaluating the energy as the separation between the bodies is increased.

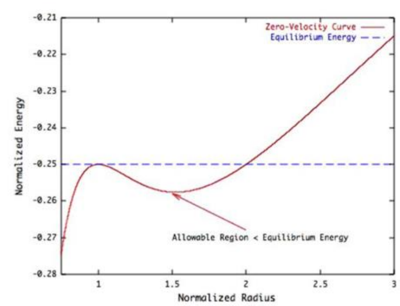

Figure 2: Constant angular momentum depiction of planar second-order orbital energy as bodies are separated. [5]

The naturally occurring stable equilibrium is identifiable as the local minimum near a radius of 1.5. The unstable equilibrium occurs at the local maximum at a radius of 1 when the bodies are nearly in contact. It becomes clear that reducing the separation must lead to collision, while increasing the separation places the bodies in the bounded, allowable region of motion. In the case of contact binaries this marks the system as successfully fissioned.

Jacobson and Scheeres demonstrate that this dynamical boundary is robust to perturbation by tidal torques and solar gravity in the planar second order system [2]. In our expansion to a nonplanar fourth order dynamical model we find that these additional perturbations increase the chaotic behavior of the system enough to breakdown this dynamical barrier and allow collision when perturbing the system from this equilibrium.

The source of this result becomes apparent by comparing the geometry of the inner unstable equilibrium for the second and fourth orders. Here we illustrate these equilibria geometries using the 1999 KW4 radar shape model, assuming a constant density [6].

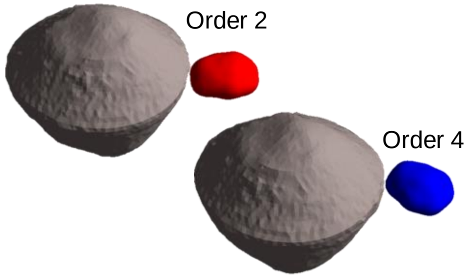

Figure 3: Illustration of nonplanar inner unstable equilibrium for 1999 KW4 evaluated at second order (upper left) and further order (lower right).

At the second order equilibrium the bodies are aligned by their principal axes due to the inherent symmetry of the second order gravity model. Expanding to the fourth order increases the significance of the asymmetries of the bodies, inducing a relative clocking away from the principal axes. Upon simulating the dynamics of the system under solar and tidal perturbations the asymmetric fourth order terms are able to pull the system across the dynamical boundary of the inner unstable equilibrium.

Analysis and Results: The breakdown of the unstable equilibrium as a dynamical boundary of contact binary fission illustrates the significance of higher order gravity and nonplanar dynamics for contact binary evolution. To explore the dynamical consequences, we perform a series of Monte Carlo analyses for a range of mass ratios and shapes of contact binaries; we then compare the statistics of binary evolutionary pathways to those found by Jacobson and Scheeres with the planar second order dynamics.

We initially perform a Monte Carlo analysis for 1999 KW4 to explore the behavior of low mass ratio binaries. The perturbations applied to the system sample from uniform distributions increasing the radial position, radial velocity, and system spin rate up to 5% above that of the inner unstable equilibrium, in addition to perturbations up to 30 degrees about each axis of the relative orientation. A set of 150 simulations are initialized sampling from these perturbations and integrated for a year long period. Each simulation is analyzed for collision, escape, and fission of the secondary asteroid. Initially we compare the rates of these asteroid fates to the results found by Jacobson and Scheeres. In Table 1 we list and compare these results.

	NPl-4th Rate	Pl-2nd Rate	NPl-4th Median Time [dy]	Pl-2nd Median Time [dy]
Collision	37%	X	<1	X
Escape	18%	58%	114	32
Secondary Fission	40%	40%	84	2.13

Table 1: Comparative rate of low mass-ratio binary fates between the nonplanar 4th order (Npl-4th) model used in this study and the planar 2nd order (Pl-2nd) results from Jacobson and Scheeres [2]. Both results show between 2-5% of systems do not disrupt over the integrated time period.

These preliminary results show that the proposed secondary fission process for dissipation of energy remains statistically significant at the same rate while the median time for secondary fission and escape events increases significantly. The slower evolution of the system under nonplanar dynamics results from the increased dynamical complexity and slower propagation of perturbations through the system. This outcome was also suggested in the original work by Jacobson and Scheeres.

In trying to redefine the dynamical boundary for fission, the results appear chaotic and unintuitive, but appears to occur at higher energy levels. This is apparent when comparing the perturbations on the system spin rate and radial position for the collisional cases, as illustrated in Fig. 3. While these perturbations are selected from a uniform distribution, there is a distinct lack of collisions for cases with large perturbations on both spin rate and radial position.

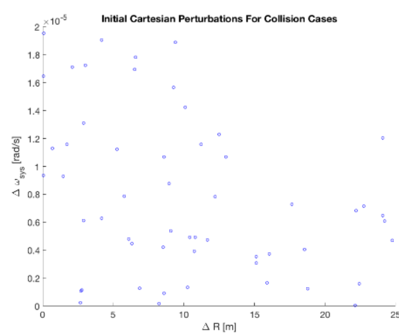

Figure 3: Perturbations on system spin rate and radial position resulting in collision of 1999 KW4 system.

Conclusions: Preliminary results suggest the importance of shape asymmetries for the fission and evolution of contact binaries. We plan to perform additional analysis of characterized contact binaries to better understand the impact of mass ratio and asymmetries on the nonplanar evolution and dynamical boundaries of contact binaries undergoing fission.

References: **[1]** Scheeres, D.J., (2007) Icarus, **[2]** Jacobson, S.A., and Scheeres, D.J., (2011) Icarus, **[3]** Hou, X., Scheeres, D.J. and Xin, X., (2016) CMDA, **[4]** Murray, C.D., and Dermott, H.F. (1999) Cambridge Press, **[5]** Scheeres, D.J., (2009) CMDA, **[6]** Ostro, S.J. et al, (2006) Science