High-Fidelity Dynamics of Post-Fission Asteroid Evolution 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: Since the identification of the 2.2-hour spin barrier in the Near-Earth Asteroid (NEA) population by Pravec et al., YORP induced spin fission has been studied as a pathway to binary asteroid formation[1]. Work by Scheeres focused on the evolution of contact binaries driven to fission by this process and identified dynamical boundaries and constraints on their evolution[2]. Later work by Walsh et al. implemented an N-body approach to rubble pile binary formation, identifying indicators of this type of fission[3]. Unfortunately, both of these models required a significant levelsof energy dissipation to match current observed binaries. In Jacobson and Scheeres 2011, the secondary fission process was proposed as a powerful method of energy dissipation; with this process accounted for they were able to develop a comprehensive map of NEA binary evolution from YORP spin fission to the currently observed population [4]. However, this work relied on assumptions of a simplified gravity model and planar dynamics.

In this work we leverage recent advancements in modelling of the full two-body problem (F2BP) in order to expand past analysis to high-fidelity and nonplanar dynamics. Using these techniques, we track the impact of the improved dynamics model on their findings, explore the dynamical boundaries at the moment of spin fission and compare models of secondary fission. We study the formation of three well-characterized NEA binaries in order to generally sample the overall population. To study the more prominent low mass ratio binaries, we model the formation of 66391 Moshup, previously known by its provisional designation 1999 KW4, and 2000 DP107. To capture the behavior of both high mass ratio binaries and contact binary fission we model the formation of a fictitiously fissioned model of contact binary 1996 HW1. For each of the three systems we use the most up to date observations and radar shape models to capture their mass distributions [5,6,7].

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.

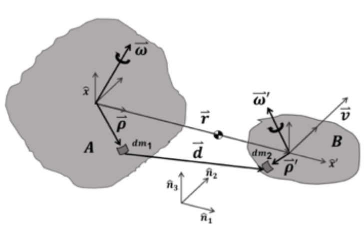

Figure 1: System diagram for the relative F2BP, where $\vec{\boldsymbol{r}}$ and $\vec{\boldsymbol{v}}$ are the relative position and velocity of the system and $\vec{\boldsymbol{\omega}}$ and $\vec{\boldsymbol{\omega}}'$ are the angular velocities of each body.

The mutual gravity potential model leverages inertia integrals of arbitrary order for simulation of arbitrarily shaped constant density bodies [8]. 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.

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

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 [9].

Fission Process: Traditionally, when studying binary fission, the fission event is defined from 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.

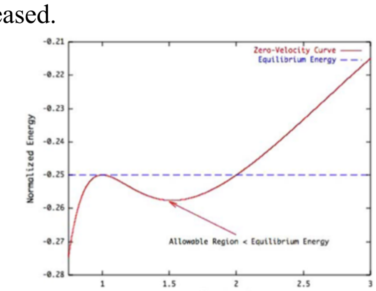

Figure 2: Constant angular momentum depiction of planar second-order orbital energy as bodies are separated. [10]

The unstable equilibrium occurs at the local maximum when the bodies are ideally in contact. Inward motion from this equilibrium results in re-collision whereas outward motion results in a chaotically captured orbit. Thus, this equilibrium is identified as the boundary for binary fission. 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 distort the associated zero velocity surface 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 Moshup (KW4) radar shape model, assuming a constant density [6].

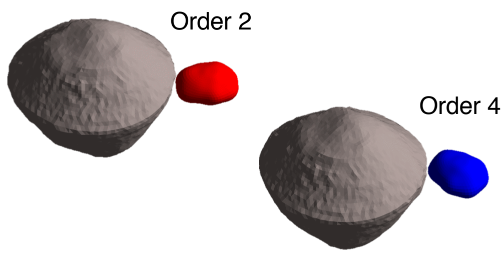

Figure 3: Illustration of nonplanar inner unstable equilibrium for Moshup (KW4) evaluated at second order (upper left) and further order (lower right).

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 torqueing 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 topologically morph the dynamical boundary such that collision can occur.

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 our three example binaries; we then compare the statistics of binary evolutionary pathways to those found by Jacobson and Scheeres with the planar second order dynamics. model and planar dynamics.

In our analysis of Moshup we identify similar rates of secondary fission and chaotic capture relative to the Jacobson and Scheeres results, Table 1. We see that the majority of the escape cases in their study become collisional cases once nonplanar, higher order gravity models are accounted for. Of additional note is increase in the time to secondary fission, which results from a difference in the contact binary style secondary fission versus the cohesion dominated model used in our study. We see a similar speedup of secondary fission, with nearly identical rates when we use the contact binary secondary fission model.

Moshup	**NP Rate**	**NP Median Time [dy]**	**JS Rate**	**JS Median Time [dy]**
Collision	43%	.5	X	X
Escape	18%	132	58%	32
Secondary Fission	37%	84	40%	2.13
Capture	3%	NA		NA

Table 1: Comparative rate of binary fates between the nonplanar 4th order (*NP*) *Moshup* model used in this study and the low mass ratio planar 2nd order (*JS*) results from Jacobson and Scheeres [2].

For HW1 we find similar results to Jacobson and Scheeres, however we find that roughly one third of the secondaries recollide with the primary due to the high order gravity model.

HW1	**NP Rate**	**NP Median Time [dy]**	**JS Rate**	**JS Median Time [dy]**
Collision	34%	<1	NA	NA
Escape	1%	146	0%	NA
Secondary Fission	0%	NA	0%	NA
Capture	65%	NA	100%	NAA

Table 2: Comparative rate of binary fates between the nonplanar 4th order (NP) HW1 model used in this study and the high mass ratio planar 2nd order (JS) results from Jacobson and Scheeres [2].

In the analysis of DP107 we initialize the secondary to fission from within the primary's equatorial crater and find the all simulated binaries either recollide or escape within a matter of days. However, when a contact binary model of secondary fission is applied this can occur quickly enough to maintain the evolutionary pathway proposed by Jacobson and Scheeres.

For all three binaries simulated we also identify significant out-of-plane excitement of the secondary upon escape, capture and secondary fission, implying more complex behavior of systems undergoing each of the events.

Conclusions: By improving the F2BP models used to analyze binary asteroid formation we are able to more robustly evaluate the evolutionary pathways of binary formation. We identify recollision as a potential post-fission results and are able to show the necessity of secondary fission for the formation of secondaries from an equatorial crater. Additionally we find that secondary fission occurs at a significant frequency regardless of modelling methodology.

References: **[1]** Pravec, P. and Harris, A.W. (2000) Icarus, **[2]** Scheeres, D.J., (2007) Icarus, **[3]** Walsh, K.J., et al. (2008) Nature, **[4]** Jacobson, S.A., and Scheeres, D.J., (2011) Icarus, **[5]** Ostro, S.J. et al, (2006) Science, **[6]** Howell, E.S. et al, (2010) BAAS, **[7]** Naidu, S. et al, (2015) AJ, **[8]** Hou, X., Scheeres, D.J. and Xin, X., (2016) CMDA, **[9]** Murray, C.D., and Dermott, H.F. (1999) Cambridge Press, **[10]** Scheeres, D.J., (2009) CMDA