CHANGES TO THE LONG-TERM DYNAMICAL EVOLUTION OF DIDYMOS AFTER THE DART IMPACT. J. W. McMahon,[1] C. Long[1], and R. Cueva[1], [1]Smead Aerospace Engineering Sciences Department, University of Colorado, Boulder, CO USA (jay.mcmahon@colorado.edu)

Introduction: The BYORP effect is one of the dominant processes that controls the dynamical evolution of small binary asteroids in the inner solar system. [1, 2] BYORP can be expansive or contractive, which is characterized by a positive or negative BYORP coefficient, B, respectively. B is determined by the shape of the secondary asteroid. It has been further hypothesized that a tidal-BYORP equilibrium can exist [3] when the orbit expansion from tides are counteracted by contractive BYORP.

Prior to the DART impact, observational evidence pointed to Didymos and Dimorphos being in a such a tidal-BYORP equilibrium state [5].

Tidal strengths are relatively unknown for small asteroids, but have been discussed in the literature [3, 4]. Based on these works, in this study, we use three different values of k_p/Q to investigate how things change with varying tidal strengths. The values used are $k_p/Q = 4\text{x}10^{-6}$, $1\text{x}10^{-5}$, and $2.5\text{x}10^{-5}$, which are listed from weakest to strongest tides.

Assuming Didymos was in a tidal-BYORP equilibrium before the impact at an equilibrium separation of 1.2 km [5], the value of the normalized BYORP coefficient of Dimorphos, B, could be determined if the tidal parameters were known. Using the values given above, the range of possible pre-impact values of B are shown in Table 1. Note for reference that the computed value of B for Squannit (the secondary of Moshup) is $B = 2.1\text{x}10^{-2}$ [2].

Table 1 - Pre-impact B values for given tidal parameters.

k_p/Q	B
$4\text{x}10^{-6}$	$-3.4\text{x}10^{-3}$
$1\text{x}10^{-5}$	$-8.6\text{x}10^{-3}$
$2.5\text{x}10^{-5}$	$-2.2\text{x}10^{-2}$

Initial Results: This work investigates how changes to the shape of Dimorphos could change B, and thus change the dynamical evolution of the Didymos binary system. Our initial work looks at what happens to B with the addition of a crater 10 m radius, 5 m deep, with a 1 m rim, on the leading edge of Dimorphos where the impact was expected to occur (pictured in Fig. 1). Starting with a perfect ellipsoid for Dimorphs, the addition of the crater changes B from 0 (for the perfect ellipsoid) to $4\text{x}10^{-2}$!

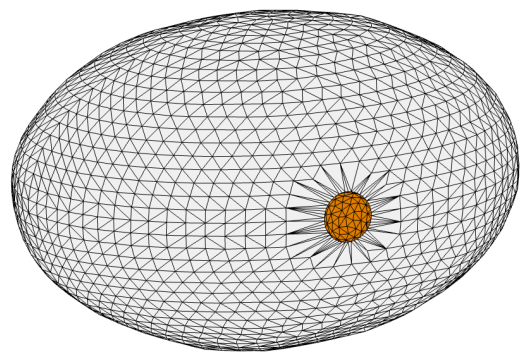

Figure 1- Illustration of ellipsoidal Dimorphos with modeled crater.

This positive change to B makes sense because we have taken surface area that was previously highly contributing to slowing down the orbit when lit since it is on the leading edge and its normal was almost perfectly aligned with the velocity direction and made it less effective by making that area non-aligned with the velocity direction.

Clearly the crater size and morphology will play an important role in determining the actual change to B. Therefore, the change may not be this size, so we also look at one or two orders of magnitude less changes to B. The results of combining the possible changes to B along with the pre-impact constraints from Table 1 result in post-impact values of B shown in Table 2. Clearly, some of the resulting B values are still negative, and some are positive, which means that Didymos could find a new tidal-BYORP equilibrium or become an expansive binary system after the impact! These results are summarized in Table 3.

Table 2 - Resulting B values for different shape change effects and tidal parameters.

ΔB / k_p/Q	$4\text{x}10^{-6}$	$1\text{x}10^{-5}$	$2.5\text{x}10^{-5}$
$4\text{x}10^{-2}$	$3.7\text{x}10^{-2}$	$3.1\text{x}10^{-2}$	$1.9\text{x}10^{-2}$
$4\text{x}10^{-3}$	$5.6\text{x}10^{-4}$	$-4.6\text{x}10^{-3}$	$-1.8\text{x}10^{-2}$
$4\text{x}10^{-4}$	$-3.0\text{x}10^{-3}$	$-8.2\text{x}10^{-3}$	$-2.1\text{x}10^{-2}$

Some initial simulations are shown in Figs 2-4 to illustrate what the dynamical evolution may look like. Note that these simulations are illustrative – they are planar, but the actual Didymos system is approximately 10 degrees away from this. Furthermore we only simulate the in-plane librational motion, and

the values are not exactly in line with those computed for Tables 2 and 3.

Table 3 - Resulting equilibrium semimajor axis (in km) for computed cases. Some cases result in an expansive BYORP (B>0) and so do not have an equilibrium.

ΔB / k_p/Q	$4x10^{-6}$	$1x10^{-5}$	$2.5x10^{-5}$
$4x10^{-2}$	∞	∞	∞
$4x10^{-3}$	∞	1.77	2.02
$4x10^{-4}$	1.22	1.39	1.59

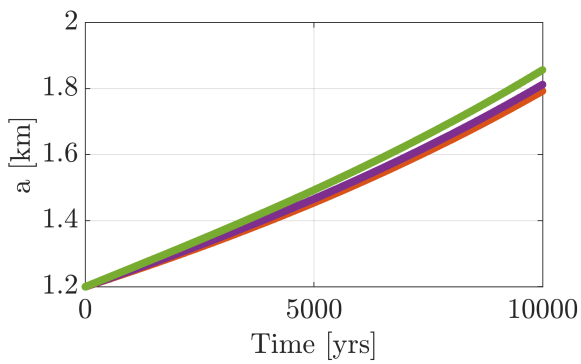

Figure 2 - Semimajor axis evolution over 10 ky with B = $4x10^{-2}$ and varying tidal parameters (listed in legend in Fig. 3).

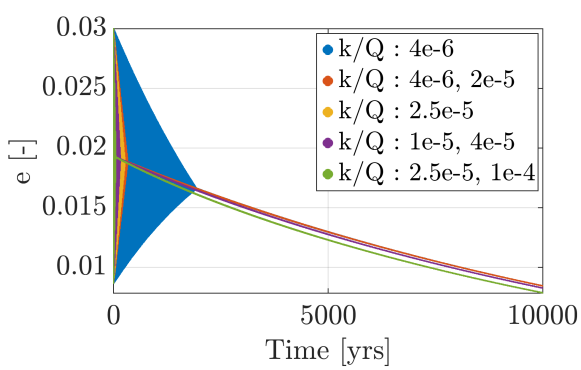

Figure 3 - Eccentricity evolution over 10 ky with B = $4x10^{-2}$ and varying tidal parameters. When two values are listed for k/Q, the first is for Didymos and the second for Dimorphos.

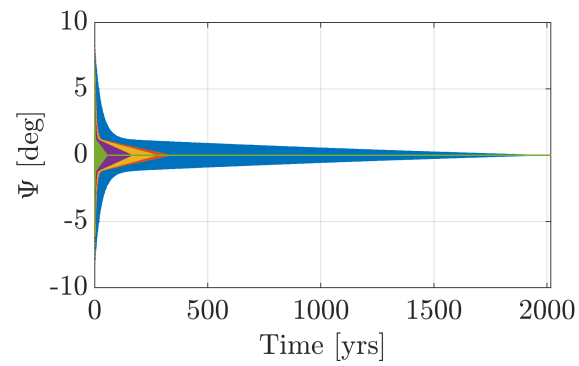

Figure 4 – Libration angle evolution over 2 ky with B = 4x10-2 and varying tidal parameters (listed in legend in Fig. 3). All libration is effectively damped within 2000 years regardless of tidal parameters.

Discussion: Changing the shape of Dimorphos - however it actually happened - will change the long-term evolution of the system. The change to the BYORP effect strength could be large enough to alter Didymos from being a stable binary in a tidal-BYORP equilibrium, to becoming an expansive binary system, or the equilibrium separation distance could simply be changed. In any case, assuming the modeled change to B is positive as shown here, the resulting orbit will be larger than the pre-impact orbit. In either case, it is interesting that the short term effect of the impact was to make the orbit smaller, but the long term effect is likely to make the eventual orbit larger.

Improvements in the modeling fidelity will be included in the final results. We will show the effect the out-of-plane dynamics could play in the evolution. BYORP will still act when the binary orbit plane is not in the heliocentric plane, although the coefficients will vary over the course of the year [2]. Furthermore, the non-planar libration can slow byorp [cuk,quillen] but for the Didymos system we will show that we do not expect this to dramatically change the secular evolution. [5] The final results will also include modeling of the known shape of Dimorphos [6] with different crater morphologies and their resulting changes to B.

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References: [1] Ćuk & Burns, 2005, *Icarus*, 176, pp. 418-431 [2] McMahon & Scheeres, 2010, *Icarus*, 209, pp. 494-509 [3] Jacobson & Scheeres, 2011, *APJL*, 736, L19 [4] Nimmo & Matsuyama, 2019, *Icarus,* 321, pp. 715-721, [5] Richardson et al, 2022, *Planet. Sci. J.,* 3(7), [6] Daly et al, 2022, *AGU Fall Meeting*.