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MINIMUM MATERIAL STRENGTH OF BINARY ASTEROID DIDYMOS-DIMORPHOS FROM THE PERSPECTIVE OF STRUCTURAL STABILITY

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Introduction: Strength properties of small celestial bodies is one factor that shapes them into the current states, and is likely important when contemplating mitigation of asteroid hazards. Estimates of such strength can be obtained from small bodies that are rotationally nearly unstable. The binary asteroid 65803 Didymos-Dimorphos system provides an opportunity for such an estimate. This system is the target of the NASA Double Asteroid Redirection Test (DART) and of the ESA Hera rendezvous mission. DART is the first asteroid deflection test [1]. Hera is the first rendezvous to a binary asteroid system and the first to explore the internal structure of an asteroid [2]. The cohesive strengths of both the fast-spinning primary (Didymos) and the secondary (Dimorphos) are key factors that could significantly affect the stability of this system and the DART impact outcome [3, 4]. To constrain the material properties as well as support the preparation and data interpretation of these missions, we investigate the structural stability and cohesive strengths of both Didymos and Dimorphos according to current observational information.

Method: We use a high-efficiency parallel *N*-body tree code, *pkdgrav* [5, 6], to simulate the full two-body dynamics of Didymos-Dimorphos system. A previous benchmarking study has validated the performance of *pkdgrav* in modeling rigid full two-body mutual gravitational dynamics [7]. In this study, we remove the rigid body assumption and treat Didymos and Dimorphos as rubble piles. The soft-sphere discrete element model (SSDEM) in *pkdgrav* is used to solve the contact interactions between particles constituting each rubble-pile model. By fine tuning the interparticle contact parameters, the effect of material strength on the evolution of Didymos-Dimorphos rubble-pile system can be then tested [3].

Several Didymos rubble-pile models with a shape matching the radar shape model [8] were constructed by using different particle arrangements and size distributions (the same as those used in [9, 10]). Dimorphos is modeled as either a solid sphere (with a radius of 81.1 m) or a rubble-pile ellipsoid (with semimajor axes, a = 104.0 m, b = 78.7 m, c = 65.8 m). Figure 1 presents two examples of our binary models.

Based on the assumption that the primary Didymos' current fast rotation is driven by the YORP spin-up effect, we explicitly simulate the spin-up process of Didymos from a slow spin state (i.e., a spin period of 5 hr) to its current fast spin state (i.e., a spin period of 2.26 hr). By assessing the creep stability of the rubble pile structures at the end of the simulations, we derive the minimum required material strength to keep the shape of each rubble-pile body.

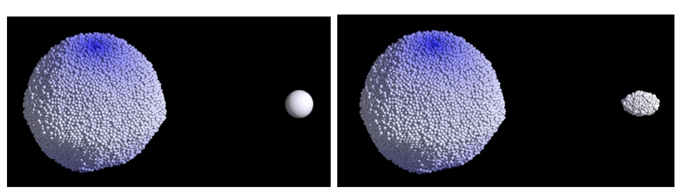

Figure 1: Rubble-pile binary models. Didymos is modelled as a rubble pile consisting of 10-meter-radius particles. Dimorphos is modelled as a solid sphere (left) and a rubble-pile ellipsoid consisting of 4- to 16-meter-radius particles (right; synchronous rotation).

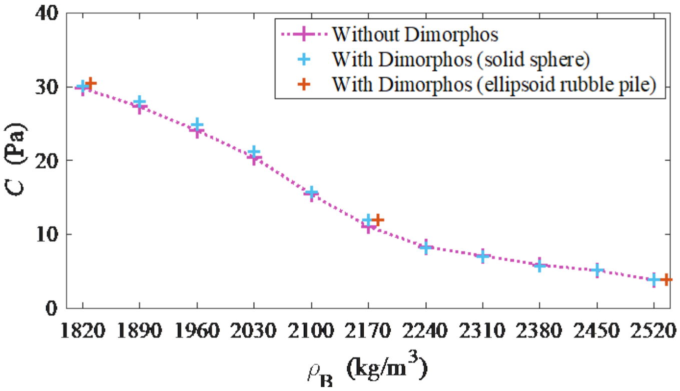

Figure 2: Minimum required bulk cohesive strength of a random monodisperse Didymos rubble-pile model (as shown in Figure 1) within the possible range of Didymos' bulk density. The colors of the plus signs represent three different cases, as indicated in the legend (in the case where Dimorphos is modelled as a ellipsoid rubble pile, the bulk density is slightly shifted in this case as we adjust the overall mass in order to match the synchronous rotation and the observed orbit).

Results: Our previous studies [9, 10] show that without Dimorphos, Didymos requires a small amount of bulk cohesion (on the order of several to tens of Pascals, depending on the rubble-pile configuration and density) to maintain its structural stability at its current spin state. Adding Dimorphos, we find that the mutual tides have some influence on the structural stability of Didymos.

Figure 2 indicates that tidal effects of Dimorphos cause an incremental increase in the minimum required bulk cohesion of 0.1–1 Pa for the considered Didymos rubble-pile model. The exact amount depends on the rubble-pile configuration, the bulk density, and the associated failure mode. As shown in Figure 2, for the cases with bulk densities smaller than the nominal value (i.e., 2170 kg/m^3), the Didymos rubble pile tends to fail internally over a large portion of the asteroid, and a larger increment is needed. For the higher-bulk-density cases where the Didymos rubble pile tends to fail through surface shedding, the tidal effect of Dimorphos on the minimum required cohesion of Didymos is negligible. Furthermore, a rubble-pile Dimorphos leads to the need for even greater cohesion, suggesting that tidal stress could be enhanced by discrete internal structures [11]. This could also be caused by the ellipsoidal shape we considered for the Dimorphos rubble-pile structure. Further investigations need to be carried out to examine the effect of Dimorphos' shape.

Our numerical experiments show that the ellipsoid rubble-pile Dimorphos can be stable with a moderate friction angle without cohesion. The exact friction might also depend on the shape of Dimorphos, which will be examined in our future study. Figure 3 shows the one-day evolution of our rubble-pile Dimorphos in the case of synchronous rotation. The deformation caused by tidal stress is extremely small (<~1 mm).

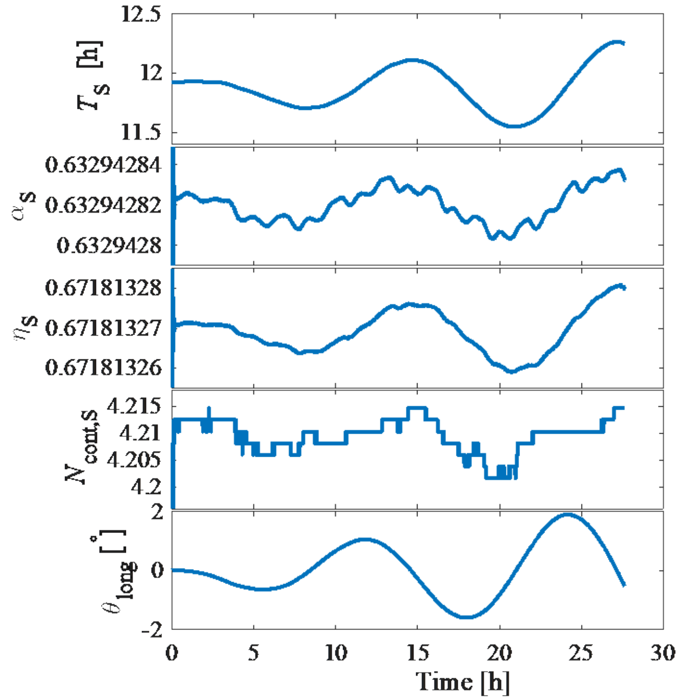

Figure 3: Evolution of the rubble-pile Dimorphos for the bulk density of 2182 kg/m^3 (from top to bottom): spin period, short-to-long axis ratio, packing efficiency, coordination number, and longitudinal libration angle.

Summary and future investigations: In this study, we derive the material and physical properties for keeping both the stable rubble-pile structures of Didymos and Dimorphos, and provide a robust way to test the full two-rubble-pile evolution of this system. As a next step, we will investigate in depth the tidal stress and evolution of this system based on the material parameters derived from the current study. We also aim at testing the DART impact within this full two-rubble-pile modeling framework to reveal the post-impact dynamics and stability of this system. Comparisons with measurements by the DART and Hera missions will help to infer the mechanical properties and history of this binary asteroid.

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