THE MYSTERIOUS LOCATION OF MARYLAND ON 2014 MU69 AND THE RECONFIGURATION OF ITS BILOBATE SHAPE. M. Hirabayashi[1], A. J. Trowbridge[2], and D. Bodewits[3]. [1]Auburn University, 211 Davis Hall, Auburn, AL, 36849, [2]Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, [3]Auburn University, Physics Department, Leach Science Center, Auburn, AL 36832.

Introduction: The close flyby of 2014 MU69 (also known as Arrokoth), a cold class Kuiper Belt Object (KBO), by the New Horizons spacecraft in 2019 showed that this object has a unique bilobate shape that consists of smoothed surfaces, hexagonal patches, and multiple crater-like features [e.g., 1-3]. Arrokoth's structure is likely to be icy and highly porous [1]. Among the crater-like features, Maryland, a circular depression enclosed by topographically high regions, is likely to be a crater with a diameter of ~7 km [1,3]. In this study, assuming that Maryland formed after the formation of Arrokoth's bilobate shape, we explore how much cohesive strength was necessary for the neck to resist structural disturbance by the Maryland impact event.

Model formulation: We combine an impact scaling model (Model I) and a dynamics and structure model (Model II). Arrokoth has a large lobe and a small lobe [4]. We assume that the large lobe is a triaxial ellipsoid with a size of 22 km × 20 km × 7 km, while the small lobe is a sphere with an equivalent radius of 6.3 km.

Model I: Applying the π-scaling relationship [5], Model I computes the linear momentum that generates the Maryland crater on the small lobe. To give constrains on the impact behavior in the gravity and strength regimes on this body, we consider two end-member target material groups. End-member A consists of a porous sand target [6] and an icy, porous target [7] in the strength regime. End-member B includes a water-ice target [8] in the gravity regime and an icy, porous target [7] in the strength regime.

Model II: This model computes the minimum cohesive strength required for the neck to avoid structural failure during the Maryland impact. To determine the structural failure condition of the neck, we use the Mohr-Coulomb yield criterion by considering the normal force to the neck's slice, f_{norm}, and the force driven by the impact force, f_{imp} (Figure 1). The angle of friction is fixed at 35° [9], and the cohesive strength is a free parameter. Because the cavity of Maryland faces almost perpendicular to the long axis of MU69 [1,3], the impactor is assumed to impact on the small lobe in the normal direction to that axis. We assume a zero-obliquity impact case for simplicity while non-zero cases may be possible [e.g., 10].

f_{imp} is the time-derivative of the change in the linear momentum of the target. The magnitude of this change is equal to that of the linear momentum of the impactor, p. The momentum transfer effect is not assessed in the present model, although it may generate an additional linear momentum [e.g., 11]. Because p may be delivered over the entire body as a form of wave propagation, f_{imp} may depend on how waves reach the neck region from the impact site. In the structure of Arrokoth, an impact-generated stress wave, which consists of elastic and plastic waves, may always be faster than a sound wave; as it grows in strength, the plastic wave catches up and surpasses the elastic wave by forming a shock wave [10]. We compute a lower limit of f_{imp} by averaging p over the time when a sound wave goes from one side to the other in the small lobe.

Integration: We integrate these models to solve the necessary cohesive strength as a function of the bulk density of the target for the defined end-member groups, given the impact velocity. We assume that the impactor's speed and bulk density are 2 km/sec and 2,000 kg/m^3, respectively, which may be consistent with a typical impact speed and density in KBOs [e.g., 12]. We note that the main purpose of the impact scaling analysis is to determine p delivered to the target. As these parameters change, the impactor's size should also be adjusted to generate a 7-km-diameter crater on the smaller lobe. This mechanism does not change p much.

Results: Figures 2 shows the cohesive strength necessary to avoid structural failure at the neck as a function of the bulk density. It requires at least a few kPa and increases to tens of kPa or larger as the bulk density grows. This implies that the derived cohesive strength of Arrokoth may be higher than that of the reported small bodies. Small rubble pile asteroids are typically observed to have cohesive strengths of ~300 Pa or lower [13], and so is the cometary nucleus of 67P [14]. There are exceptional objects having cohesive strength up to 1 kPa [15]. A ballistics analysis of the Deep Impact ejecta also showed that the cohesive strength of the nucleus of comet 9P/Tempel 1 may likely be less than~340 Pa [16]*. Also, the cohesive strength of ice rubbles is around 1 kPa, depending on the shear speed [17].

Discussion: Our model suggests a discrepancy between the cohesive strength of Arrokoth and that of small bodies observed at high resolution. One explanation is that Arrokoth's neck is strong enough to resist structural disturbance by the Maryland impact. This explanation, however, is inconsistent with the present knowledge about the cohesive strength in small bodies.

Another scenario may be that the Maryland impact caused structural failure of the neck and broke it. These two lobes can freely move until they settle into a stable shape configuration where the energy is lowest [14]. We compare the energy levels of two shape equilibria that Arrokoth possibly had before the Maryland impact event [18]. Shape 1 corresponds to the current configuration in which the small lobe is resting on the long axis of the large lobe. Shape 2 is a condition in which the small lobe is on the intermediate axis of the large lobe. This shows that Arrokoth has never experienced Shape 2 in its history. Thus, it is possible Arrokoth originally had Shape 1, the neck broke up, and each component was slightly reconfigured due to the Maryland impact.

Because this shape sorting process should be satisfied anytime, the observed spin state may imply the condition during the formation of the original bilobate shape of Arrokoth, which is consistent with the interpretation by [1, 19, 20] but may depend on the impact conditions [21]. Also, the Maryland impact may not significantly change Arrokoth's rotational state. We use this sorting mechanism and the condition of the body's fission as a constraint on the structure of Arrokoth. This leads to a bulk density between 300 kg/m^3 and 500 kg/m^3 (Figure 3), which is consistent with [22] and the bulk density of the nucleus of 67P [23,24]

*We note that [16] introduced an effective strength, which was defined as K_2Y. $K_2 > 30$ in our analysis, and they estimated an upper limit of the effect strength as 10 kPa, leading to a cohesive strength of this nucleus less than ~340 Pa.

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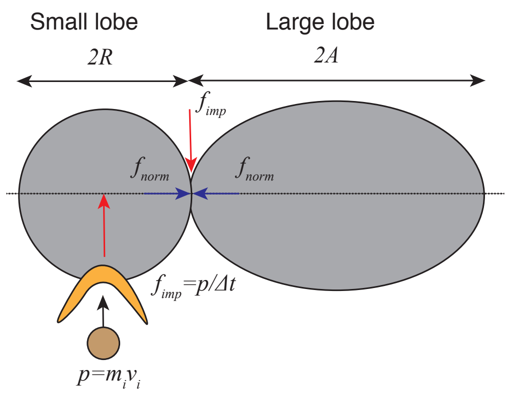

Figure 1. Schematic of impact scenario for the Maryland crater.

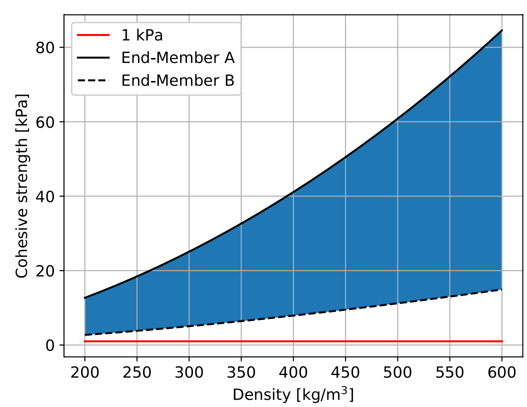

Figure 2. Necessary cohesive strength as a function of the bulk density of the target.

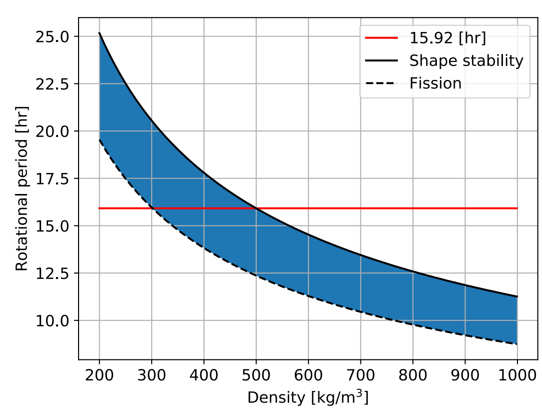

Figure 3. Arrokoth's shape condition given the fission conditions and the shape stability that Shape 1 is the primordial state.