FORMATION OF EXTREMELY ELONGATED BODIES BY TIDES: APPLICATION TO THE INTERSTELLAR OBJECT 1I/`OUMUAMUA. Y. Zhang[1], P. Michel[1] and D. C. Richardson[2], [1]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France, [2]University of Maryland, College Park, MD 20742, United States.

Introduction: Astronomical surveys, such as Pan-STARRS, LONEOS, WISE, and Catalina, etc., reveal a considerable amount of extremely elongated small bodies with a short-to-long axis ratio $c/a < 1/3$ in the Solar System [1,2]. The first and only discovered interstellar interloper, 'Oumuamua (1I/2017 U1) exhibits a more unusual axis ratio $c/a < 1/5$. Among the possibilities, collisional events are unlikely to produce an object with an axis ratio $c/a < 1/3$ [3], as are thermal YORP-induced rotational deformations [4], which leaves tidal disruption as the most probable mechanism to form such an extraordinary shape [5]. Here we numerically investigate the fragmentation outcomes of tidal disruption events and discuss the range of shapes produced with different material strengths.

Methodology: We use a high-efficiency SSDEM code, *pkdgrav*, to investigate the dynamical behaviors of self-gravitating rubble piles during close planetary encounters. A soft-sphere discrete element model including 4 dissipation/friction components in the normal, tangential, rolling, and twisting directions is applied for computing particle contact forces [6,7]. These quantities determine the magnitude of the material shear strength.

Simulation setup: We physically simulate the disintegration of self-gravitating rubble piles that approach an Earth-type planet on a parabolic orbit with various perigee distances. The rubble-pile object is modelled as a spherical granular assembly consisting of ~20,000 particles with a –3-index power-law particle size distribution. The initial bulk density is set to 2 g/cc and radius to 100 m. The mass of the planet is assumed to be $1M_E = 5.97 \times 10^{24}$ kg with radius $1R_E$ = 6378 km, for which the theoretical tidal failure limit for a cohesionless rubble pile with a friction angle of 30° and a bulk density of 2 g/cc is about $1.9R_E$ [8]. As the tidal failure limit d_{limit} is proportional to the bulk density ρ_o of the object and the planetary or stellar bulk density ρ and size R as $d_{\text{limit}} \propto R(\rho/\rho_o)^{1/3}$, the simulation results can be scaled to different rubble-pile bodies and planet or star types. Additional simulations of the tidal disruption of a rubble pile approaching a star give similar fragmentation results when the bulk density and size is set to the right scale.

Results: The simulation results show the same behavior of the rubble-pile body in response to tidal forces as found in previous studies [5]. Due to the intrinsic material shear strength, the rubble-pile object can only be tidally disrupted at a distance notably lower than the theoretical tidal failure limit (i.e., $1.9R_E$ in this case). For weak encounters, where the perigee distance is close to the tidal failure limit, the rubble pile is slightly distorted to a prolate shape when passing by the planet. The distortion of the object becomes more severe with a smaller perigee distance. When the perigee distance is smaller than $1.5R_E$, the parent body is spun up, heavily distorted and then disrupted by planetary tides. Since tidal forces increase dramatically with decreasing perigee distance, the parent body is subject to more intense disruption and is split into many more fragments for a closer orbit.

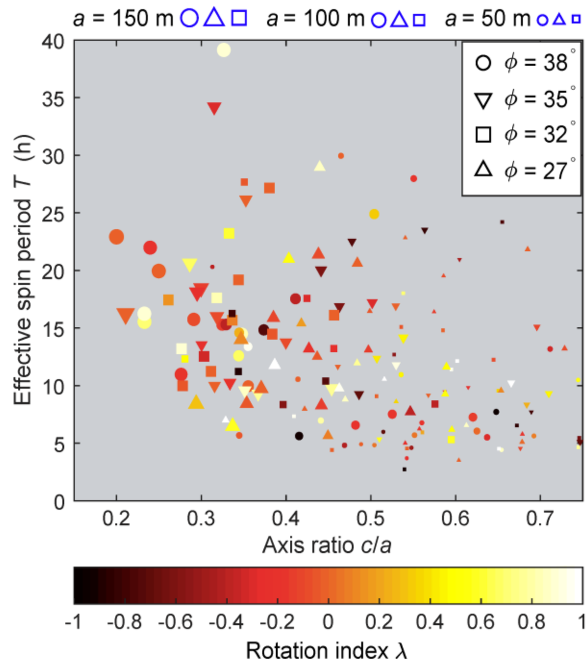

Figure 1 Effective spin period and axis ratio distributions of fragments for different material friction angles ϕ. The symbol size denotes the semimajor axis a, and color denotes the rotation state, where λ = 1, 0, and –1 indicate the short-, intermediate-, and long-axis rotation states, respectively, and values in between indicate non-principal-axis rotation states.

We run the simulations until all the fragments have settled down to stable configurations. The resulting fragments have shapes that are typically much more elongated than in previous studies that did not include frictional forces [9]. Many fragments are produced during the strong encounter cases. Figure 1 presents the shape and rotation state of the resulting fragments for tidal disruption at a perigee distance of $1.05R_E$, and

Figure 2 shows an example of an elongated fragment. Generally, larger fragments have more extreme axis ratios and longer rotation periods, and almost all of the fragments are tumbling rotators. More elongated fragments can be formed when using a higher friction angle ϕ, as shown in Fig. 1 (elongation increases to the left). Extreme elongated fragments with $c/a \sim 0.3$ can form even for a friction angle as low as 27°. This indicates that production of elongated fragments by strong tides is robust.

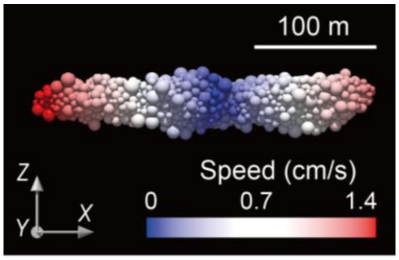

Figure 2 Example of an elongated fragment (size: 265 × 89 × 55 m) formed by tidal disruption. The colors show the bulk rotation, about 16.2 h in this example.

Conclusion: Our study provides a possible formation scenario for the observed extremely elongated small bodies. The fragments produced by tidal disruption primarily have prolate shape. This is consistent with the shape distribution of small Solar System bodies, among which none of the oblate bodies is observed to have an axis ratio $c/a < 0.4$ while some prolate bodies have an axis ratio $c/a \sim 0.2$ [10].

The interstellar object ‘Oumuamua can also be formed through tidal disruption. The energy injected into the resulting fragments by the tidal forces can lead to ejection from their original planetary system if a rubble-pile object closely passes by its host star on a nearly parabolic orbit. The close encounter with the host star would cause sublimation of volatiles, producing interstellar objects resembling ‘Oumuamua's spectroscopic properties [11].

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References:

[1] Cibulková H. et al. (2018) *A&A*, *611*, A86. [2] McNeill A. et al. (2019) *AJ*, *157*, 164. [3] Schwartz S. R. et al. (2018) *NatAs*, *2*, 379. [4] Zhang Y. et al. (2018) *ApJ*, *857*, 15. [5] Bottke W. F. et al. (1999) *AJ*, *117*, 1921–1928. [6] Schwartz S. R. et al. (2012) *Granular Matter*, *14*, 363–380. [7] Zhang Y. et al. (2017) *Icar*, *294*, 98. [8] Holsapple K. A. & Michel P. (2008) *Icar*, *193*, 283–301. [9] Richardson D. C. et al. (1998) *Icar*, *137*, 47–76. [10] Ďurech, J. et al. (2010) *A&A*, *513*, A46. [11] Zhang Y. et al. (2019) *In preparation.*