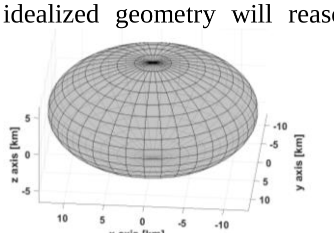
MERGER AND SPINDOWN OF (486958) ARROKOTH BY COLLISIONS. Xiaochen Mao[1], William B. McKinnon[1], K.N. Singer[2], J.T. Keane[3], S.J. Robbins[2], P.M. Schenk[4], J.M. Moore[5], S.A. Stern[2], H.A. Weaver[6], J.R. Spencer[2], C.B. Olkin[2], and the *New Horizons* Science Team; [1]Dept. Earth and Planetary Sci. and McDonnell Center for the Space Sci., Washington University in St. Louis, Saint Louis, MO 63130 (mao@levee.wustl.edu), [2]SwRI, Boulder, CO 80302, [3]GPS, Caltech, Pasadena, CA 91125, [4]LPI, Houston, TX 77058, [5]NASA Ames Res. Center, Moffett Field, CA 94035, [6]JHUAPL, Laurel, MD 20723.

Introduction: The *New Horizons* fly-by of Arrokoth (formerly 2014 MU_{69}, or 'Ultima Thule') revealed an ancient, contact binary planetesimal [1,2]. From a detailed shape model, the principal axes of each individual lobe have been found to be aligned to within a few degrees [2], a configuration that suggests a co-orbiting Arrokoth before the coalescence of its two lobes [3]. A random walk due to collisions with other heliocentric bodies is one mechanism proposed for KBO binaries to 'harden' and merge to form a single bilobate body [3,4]. In addition, Arrokoth's present-day spin period (15.92 hr) is slower than that predicted from their mutual gravitational pull (11.26 hr), assuming the critical rotation rate for a comet-nucleus-like density of 500 kg m^{-3} [3]. While Arrokoth may simply be less dense than this, it is worth exploring whether collisions with other KBOs could have substantially altered its spin state over time. Here we update and expand a study of Arrokoth's possible spindown by impacts [5], following the Monte Carlo approach we have developed for Ceres and Vesta [6].

Idealized shape of Arrokoth and model results: The physical treatment for random impacts onto a spherical or a spheroidal body are documented in [6]. For simplicity, we first idealize Arrokoth as an oblate spheroid (Fig. 1, top; Table 1), fixing its density and moment-of-inertia to present-day values; in doing so its surface area is only ~7% larger than that of the best-fit ellipsoids of the 2 lobes [2]. Hence we expect a simulation of random impacts on the surface of this idealized geometry will reasonably approximate, in terms of angular momentum evolution, that of a more realistic geometry (a supposition we test below).



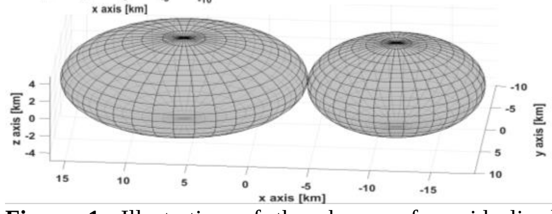


Figure 1. Illustration of the shapes of an idealized Arrokoth (top) and a more realistic contact binary geometry (bottom). Both models possess the same moments of inertia, and similar surface areas.

Table 1. Parameters for an oblate Arrokoth.

Equatorial radius[1]	13.1 km
Polar radius[1]	6.6 km
Surface area	~1500 km^2
Mass, M	2.4×10^{15} kg
Density (ρ)	500 kg m^{-3}
"Initial" rotation period (P)[2]	11.26 hr
Number of impacts	100
Impactor diameter range ($d_{\rm imp}$)	[10 m, 2 km]
Impact speed range[3]	[100 m/s, 1 km/s]

[1] Assuming 2:1 axis ratio [2]
[2] Rotation period = 15.92 hr × $(250/\rho)^{0.5}$ [3]
[3] Impact velocity distribution of cold classical Kuiper belt objects (CCKBOs) [7]

Crater counts on Arrokoth imply a dearth of small impactors, but the singular "Maryland" crater stands out because of its large size (7-km wide) [1,2]. From crater scaling in [7], with a typical impact speed ~300 m/s, "Maryland" could have been created by an impactor ~1 km wide. For 100 impacts within the chosen range assuming $dN/dD \propto D^{-1.75}$ [2,7], where $N(>D)$ is the number of impactors with diameters greater than D, about 1 of them is expected to be > 1 km. Thus, we do not exclude Maryland-like craters in our impact simulations. We also follow three recent disruption criteria in the literature [from 8], to test for potential catastrophic breakup.

Figure 2 shows the results after 3000 Monte Carlo simulations, at first only considering mass loading (no ejecta loss) from cold classical impactors only. The final spin distribution is 11.2 ± 1.1 hr (1σ), with 0.6% actually spun down to or beyond 15.92 hr. About 20% of the runs have a final spin increase or decrease by more than 1 hr. The total mass loading is only 0.06 ± 0.05% (1σ) of M, but the collective effect on "Arrokoth's" spin is enhanced by the relatively large impact velocities, compared with its surface rotational velocity. Minimal ejecta is actually a justifiable end-member for impacts into highly porous surfaces [9], but we also consider the angular momentum fate of ejecta, following our updated model for angular momentum "drain" [6]. We find that other than the overall net-decrease in Arrokoth's mass (average total ejecta loss ~(4.0 ± 1.9) × integrated impactor mass), the final spin period distribution is not much different (11.1 ± 1.0 hr). This is expected because the escape velocity of Arrokoth is ~5 m/s, much lower than even the minimum impact velocity from the discrete

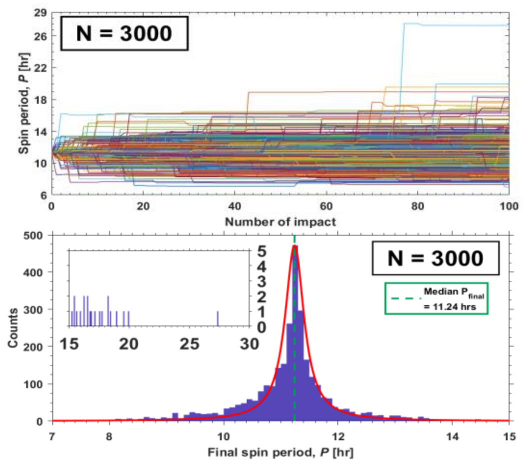


Figure 2. Top: All spin evolution curves for 3000 simulations, starting from P = 11.26 hr. Bottom: Final spin distribution (0.1 hr bin) and its Lorentzian fit in red.

distribution in [7], thus the escaped ejecta is unable to carry away large amounts of rotational angular momentum.

Finally, we "mix in" ~30% hot classical impactors (with faster impact velocity, from 0.2 – 4.0 km/s [7]) in the simulation (not considering ejecta loss). Our results show a wider distribution of Arrokoth's final spin, 10.9 ± 1.8 hr (1σ), and also an increase in the probability of its spindown to >15.92 hr (~1.5%) and of net change by >1 hr (~31%). No disruption is predicted.

Improved Arrokoth geometry: We have implemented a more realistic geometry for our spin evolution model (Fig. 1, bottom; Table 2), despite the complications arising accruing to ejecta evolution from such a shape. The great linear extent of Arrokoth's true shape may provide a greater moment arm for impact perturbations to its spin. Another advantage is that this geometry allows a more realistic calculation of the catastrophic disruption risk, which is greater for either lobe individually compared with that for the spheroidal Arrokoth. We assume the probability of an impact striking either lobe is proportional to the lobe's surface area, i.e., ~62% of impacts collide with Large Lobe. Then on each lobe, we randomly select impact points on the spheroid (see [6]). Near the neck region, however, we check the trajectory (ray path) of a given impactor: if the other lobe is on the path of its trajectory, we re-select an impact direction until the

Table 2. Additional Parameters for a Bilobate Arrokoth.*

Large Lobe radii[1]	(10.1, 4.7) km
Small Lobe radii[1]	(7.3, 4.9) km
Total surface area	~1400 km^2
Mass (M_2)[2]	1.55 × 10^{15} kg
Center-of-mass separation[3]	17.4 km

[1] Assuming both lobes are oblate spheroids, from best-fit ellipsoids in [2]
[2] 500 kg/m^3 assumed
[3] Assuming two touching lobes, along their long axis

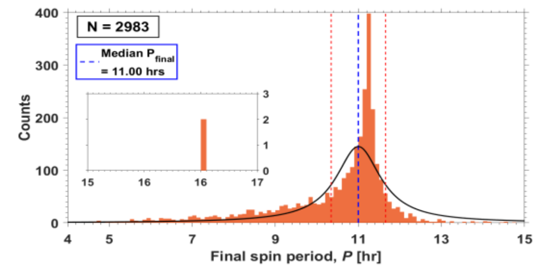


Figure 3. Final spin distribution from the new model. Out of 3000 simulations, 17 of them end with P < spin limit (~4.66 hr for the assumed density) so they are not included in the Lorentzian fit. Interquartile range = 10.3 – 11.7 hr (red dashed lines).

pathway is "clear".

Figure 3 shows the results for another 3000 simulations with this more realistic Arrokoth shape. Ejecta is again assumed retained, and impacts are from other cold classical KBOs only. The overall distribution of final spin is skewed toward faster rotation (10.5 ± 1.4 hr (1σ), skewness ~ −1.4), and out of 2983 runs only 2 are slowed beyond 15.92 hr (in both runs Arrokoth experiences 2 impactors ≳ 1.5 km), but ~30% of the outcomes Arrokoth experiences at least 1 hr net change in spin period. The skewness may be an artifact of our impact trajectory acceptance criterion. No disruptions occurred during the simulations.

If we assume that all ejecta with velocity greater than Arrokoth's mean escape velocity is lost, the final spin distribution changes little: 10.9 ± 1.5 hr; ~29% of the runs have net spin change >1 hr, and 0.4% of the time Arrokoth is slowed to >15.92 hr.

Conclusions: Impacts are shown to play a potentially important role in Arrokoth's angular momentum evolution over time. Although major changes in spin are unlikely, i.e., spindown from an ~11 hr to a 16 hr period due to impacts alone is probabilistically very unlikely, neither should one assume today's rotation is primordial. We suspect that most important role for heliocentric impacts actually occurred when Arrokoth was a co-orbiting binary. The greater the binary separation, the greater the relative angular momentum input to the system for a given impact, the cumulative effect of which could be important for ultimate binary merger (under study).

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