**COLLISIONS WITH SMALL CLASSICAL KUIPER BELT OBJECTS ARE NOT SUFFICIENT TO CAUSE SUBSTANTIAL SPIN CHANGES TO ARROKOTH.** 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]JPL, Pasadena, CA 91109, [4]LPI, Houston, TX 77058, [5]NASA Ames Res. Center, Moffett Field, CA 94035, [6]JHUAPL, Laurel, MD 20723.

**Introduction:** The density and angular momentum state of bilobate Kuiper belt object (KBO) Arrokoth are some of the compelling questions raised by the 2019 *New Horizons* flyby [1-4]. As indicated in [3], if the observed rotation of 15.92 hr were the synchronous spin of Arrokoth's Large Lobe (LL) and Small Lobe (SL) at merger, then these two lobes would have to possess extremely low density of 250 kg/m$^3$, assuming no induced stresses on the contact surface or "neck." Any bulk density greater than 250 kg/m$^3$ would imply a synchronous spin period shorter than today's. That said, Arrokoth might have experienced spindown since its merger. The exact bulk density ($\rho$) of Arrokoth remains unknown, but geophysical modeling of gravitational slopes suggests a range for this quantity [2]. Considering comet 67P/Churyumov-Gerasimenko [5] as a density analogue (~500 kg/m$^3$) to Arrokoth, under this circumstance 30% of Arrokoth's "initial" angular momentum would need to be lost to accommodate its observed spin today. Despinning (or spin change) is not an unusual phenomenon for small bodies; indeed, both Ceres and Vesta may have been despun by impacts [6-7]. In this work, we investigate the probabilities of Arrokoth's spindown (or spinup) from the time of the lobes' merger to the present day by impacts from small KBOs and discuss whether it is sufficient for impacts alone to cause such a substantial angular momentum loss.

**Arrokoth modeled as a triaxial ellipsoid:** Impact simulations demonstrate that the moment-of-inertia (MOI) of a target body is a dominant term in determining any change in angular velocity [e.g., 6]. Thus, we intentionally adopt a dynamically-equivalent triaxial ellipsoid (see Table 1) to represent the bilobate

**Table 1. Parameters for dynamically-equivalent triaxial Arrokoth.**

| | |
|---|---|
| Semi-major axes ($a$, $b$, $c$) | (18.0, 9.1, 4.9) km |
| "Initial" rotation period ($P$)[1] | 11.26 hr |
| Density ($\rho_{triaxial}$)[2] | 581 kg/m$^3$ |
| Number of impacts | 100 |
| Impactor diameter range ($d$) | [10 m, 1 km] |
| Impact speed range[3] | [~5 m/s, 5.3 km/s] |

[1] Rotation period = 15.92 hr × $(250/\rho)^{0.5}$ [3]
[2] Matching Arrokoth's MOI requires $\rho_{triaxial}$ = 581 kg/m$^3$ × ($\rho$/500)
[3] Impact velocity distribution of cold and hot classical Kuiper belt objects ([11], courtesy by S. Greenstreet)

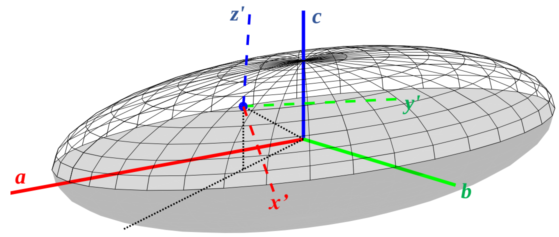


**Fig. 1.** Dynamically-equivalent triaxial Arrokoth. Three colored solid lines are the principal axis directions of the ellipsoid. The dotted lines denote the local coordinate system at the impact location (as an example) that has a colatitude of 65° and longitude of 27°. Note the local normal vector (dashed blue line) does not pass through the origin and local *x'*-axis (dashed red line) does not follow the tangent of the meridian.

Arrokoth in our model (note that quotation marks are used here to distinguish between the modeled triaxial body and the actual Arrokoth). Such a shape representation largely reserves the cross-sectional areas along each principal axis and results in only a 5% larger volume than Arrokoth. Adopting an ellipsoidal shape avoids geometric complexities arising from trying to model impacts and ejecta transport in the neck region: every point on this ellipsoid can be parametrized, along with other quantities such as the normal vector and the tangent line along the meridian (see Fig. 1), all of which ease the calculation after a given impact onto "Arrokoth." We then adjust the density of this triaxial ellipsoid to match Arrokoth's MOI at a given density.

Regarding the locations of simulated impacts on "Arrokoth," they are equivalent to random point generation on a triaxial ellipsoid. We adapted a well-vetted Monte Carlo method [8] to generate a desired number of points on "Arrokoth" as impact locations.

**Details of Monte Carlo impact simulations:** Quantifications of impact parameters involve putative crater counts on Arrokoth [9], crater-impactor scaling [10], impact velocity distribution [11], and the small KBO size-frequency distribution [12]. In the simulation, impactors have diameters $d$ from 10-to-1000 m following $N(>d) \sim d^{-0.75}$, where $N(>d)$ is the number of KBOs with diameters greater than $d$. Additionally, out of 100 simulated impacts, close to 76% are from dynamically cold classical KBOs (these have lower impact speeds) and the rest are assumed to be represented by dynamically hot KBOs (e.g., Plutinos), which have higher impact speeds. Different from [4], we impose equal density of the impactor and "Arrokoth," whatever that may be. Ejecta loss is also calculated with

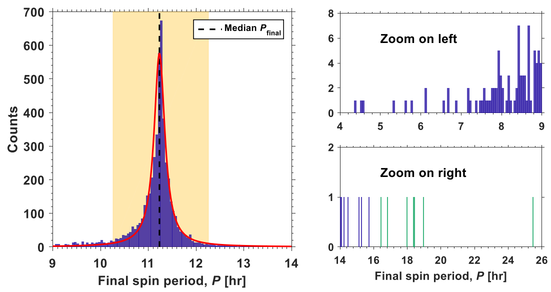


**Fig. 2.** Final spin distribution of "Arrokoth" from 5000 simulations. Dashed line is the median value 11.23 hr and the shaded region denotes ±1 hr zone from 11.26 hr (91% of all simulations). Red curve is the Lorentzian fit to the data with interquartile range (IQR) = 11.02 – 11.35 hr. Only 7 simulations (green symbols in the lower right panel) succeed in slowing down to 15.92 hr through impacts.

scalings in [13], though we later relax this by incorporating compression scaling where appropriate (this suppresses ejecta [10]). Lastly, the disruption energy threshold for porous asteroids in [14] helps us to separately compare the required disruption energies for SL and LL with the incoming impactor's kinetic energy and check for such potentially catastrophic events.

**Nominal model results:** Figure 2 shows the results from our nominal model setup. Surprisingly, out of 5000 simulations, merely 0.1% managed to successfully despin to 15.92 hr and beyond, starting from 11.26 hr. Rather, more than 90% of the time "Arrokoth's" final spin is changed by less than 1 hr, with the interquartile range (IQR) generally limited to ±15 min. This clustered spin distribution is of course connected to dominance of small impactors (on average, 85 impactors are expected to be smaller than 100 m wide); yet, our simulation does not exclude the formation of Maryland-like craters on "Arrokoth." In fact, according to scaling in [10] (assuming 70% porosity), 20% of the largest impacts among all simulations could form craters of Maryland-scale. This fraction increases to over 60% if we adopt the nominal sand-like scaling from [11]. None of these impacts causes disruption, however. Therefore, based on disruption criterion [14], we do not expect the formation of Maryland to severely disturb Arrokoth's configuration, at variance with [15].

In a companion abstract [16] we discuss the possibility craters on Arrokoth form in the compaction regime [10]. In this regime crater form mostly by crushup of porosity and ejecta is suppressed. We test this by assuming that no ejecta escapes for gravity-scaled sizes $\pi_2 > 10^{-6}$ , and rerun our nominal simulations. Results indicate little statistically distinguishable distributions of the final spin of "Arrokoth."

**Does Arrokoth actually have low bulk density?** Our nominal model results only marginally justify Arrokoth's spindown by small KBOs alone, because of insufficiency of small KBO angular momentum transfer.

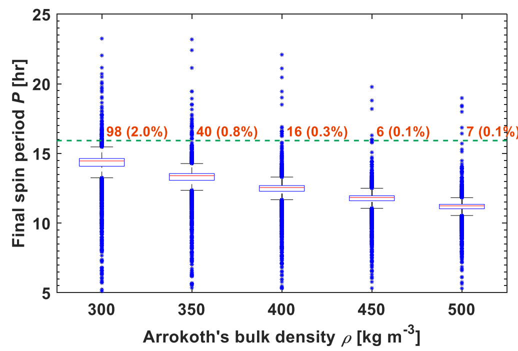


**Fig. 3.** Boxplot of spin distributions as a function of Arrokoth's density. Red lines are the median values in each suite of simulations, the box width equals IQR, and the whisker length is 1.5×IQR. Green dashed line indicates Arrokoth's observed spin.

As Arrokoth's actual density remains unknown, we proceed to investigate how this parameter might affect our interpretation of Arrokoth's proposed spindown history by rerunning the simulations with different density values from an admissible range [3], and make a boxplot in Fig. 3 for comparison.

One apparent trend in Fig. 3 is the increasing fraction of simulations with final spin greater than 15.92 hr, from 0.1% at the nominal density of 500 kg/m$^3$ to 2.0% at the lowest tested density of 300 kg/m$^3$. Not shown here, Arrokoth's despinning probability actually rises to closer to 50% as its density approaches 250 kg/m$^3$. Overall, the probability of Arrokoth's spindown by impacts alone is nonetheless low.

**Discussion:** Our Monte Carlo impact simulations indicate that under the nominal conditions, Arrokoth's spin is little affected by collisions, and is unlikely to have undergone substantial spindown by impacts from small classical KBOs. Arrokoth may indeed have a very low bulk density, or its post-merger spin may have been modified by other physical mechanisms, such as gas drag. Additional factors may influence the probability of Arrokoth's proposed collisional spindown, however, such as a steeper slope of KBO size-frequency distribution [17], a larger upper limit of impactor size (cf. Table 1), and the singular Maryland-forming event, all of which are being investigated.

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