THE GEOPHYSICAL ENVIRONMENT OF (486958) ARROKOTH.

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Introduction: On 1 January 2019, NASA's New Horizons spacecraft performed the first flyby of a small Kuiper Belt Object (KBO), (486958) Arrokoth (formerly 2014 MU_{69}). New Horizons revealed a fascinating contact binary, likely preserving some of the earliest epochs of solar system formation and evolution [1–4].

In the year since the flyby, the New Horizons team has significantly refined the shape model of Arrokoth using multiple techniques [1–2, 5–8]. These shape models show Arrokoth to be a flattened, bilobed, contact binary (overall dimensions: 36 × 20 × 10 km), with the larger lobe having roughly twice the volume of the smaller lobe. Arrokoth's spin period is 15.92 hours [5]. There are no direct measurements of Arrokoth's mass.

In this work, we investigate the geophysical character of Arrokoth using the newest global shape model. We calculate the predicted surface gravity, geopotential, surface slopes, moments of inertia, and more. These fundamental properties control a number of geologic processes—from mass wasting to tectonics. Our goal is to understand the formation and evolution of this small KBO. We will present new results from our analyses, including correlations between geophysical quantities and surface features, new estimates for the bulk density of Arrokoth, and more.

Surface Gravity, Geopotential, and Slopes: We calculate a variety of geophysical quantities accounting for the best, current Arrokoth shape model [2, 5–6] using the polyhedron method commonly implemented for small bodies [e.g., 9–13]. We assume uniform bulk density and principal axis rotation.

Figure 1 shows the derived geophysical quantities for Arrokoth, assuming a bulk density of 240 kg/m^3 (justified below). With this bulk density, the surface accelerations are approximately 0.5 mm/s^2. Fig. 1A shows the highest-resolution image of Arrokoth (CA06 LORRI image, with a resolution of 33 meters/pixel). Fig. 1B shows the newest shape model in the same viewing and lighting configuration as Fig. 1A. Fig. 1C shows the geopotential elevation—which is the

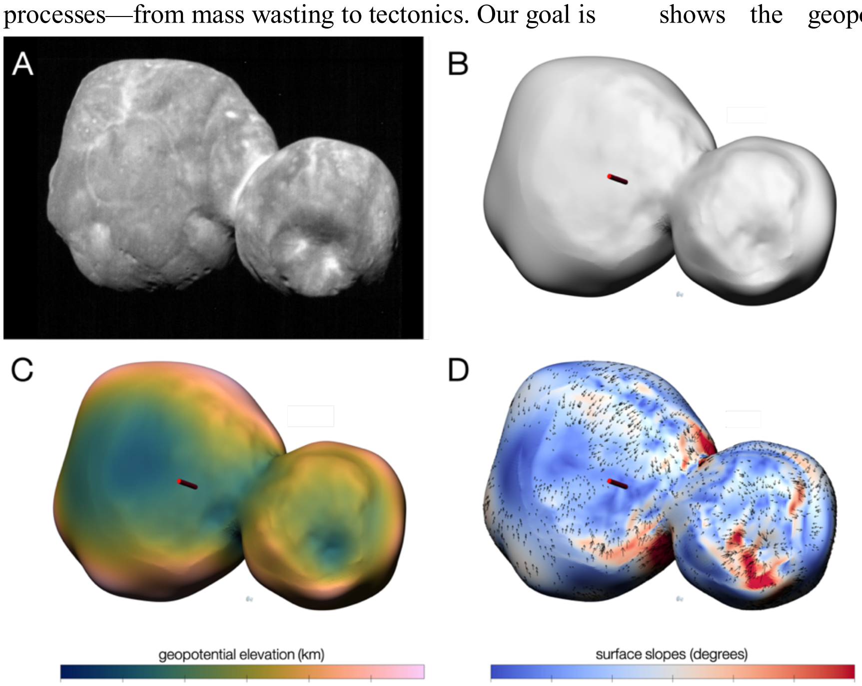

Figure 1 | Derived geophysical properties of (486958) Arrokoth. *A, New Horizons image of Arrokoth (NASA / JHUAPL / SwRI / Tod Lauer). B, Global shape model of Arrokoth. C, Geopotential elevation. D, Surface slopes. Arrows indicate the downslope direction. In all panels, the Arrokoth shape model is shown with approximately the same viewing and illumination geometry as in Fig. 1A. The red vector is the spin axis, which runs through the derived center of mass and is parallel to the maximum principal axis of inertia.*

elevation with respect to a geopotential (in this case, the geopotential minima is in Arrokoth's neck). Geopotential elevation is more geologically meaningful than the radius (i.e., geometric elevation). The geopotential elevation variations are small (<3 km), with geopotential highs at the "equators" of each lobe, and geopotential lows at the "poles" of each lobe and in the neck between the two lobes. This means that if material can flow downslope it will naturally move to higher latitude and into the neck. This may explain certain geologic units on Arrokoth—particularly bright features which are often correlated with geopotential lows [1–2]. These correlations are further reinforced in maps of the surface slope (Fig. 1D).

Moments of Inertia: The two lobes of Arrokoth are well-aligned (Fig. 2) [1–3]. The principal axes of inertia of each lobe are nearly parallel to the corresponding principal axes of the other lobe, and of the entire object as a whole. We quantify this alignment by taking the sum of the rotation angles required to align the two sets of principal axes. The sum can span 0° to 180°, and randomly oriented lobes tend to have values near 90°. Arrokoth's principal axes are aligned to within 6°. This alignment is very unlikely by chance, suggesting it is the result of a formation or evolutionary process. The current favorite hypothesis is that the two lobes tidally locked prior to a gentle merge [1–3]. We will discuss this and other hypotheses.

Inferring Arrokoth's Density: While there are no direct measurements of Arrokoth's mass, it is possible to place bounds on it through geophysical inference [1–3]. For asteroids and comets, the statistical distribution of hill slopes is often related to the bulk density of the object [14–15]. In short, if one calculates the slope distribution for a range of possible bulk densities, the variance of the slope minimizes at the actual density. We performed this analysis on Arrokoth, and inferred a density of 240 kg/m^3 (with a 1σ range of 160–450 kg/m^3). This low density is consistent with other estimates of the density based on neck-strength and the assumption that regolith is bound.

This low inferred density may have important implications for the formation and evolution of small bodies across the solar system. Even the +1σ density (450 kg/m^3) is lower than the measured bulk densities of Jupiter family comets (e.g., 67P/Churyumov-Gerasimenko: 532±7 kg/m^3 [16]), and is more comparable to the low densities of some Saturnian ring moons (e.g., Methone: 307±30 kg/m^3 [17]) which are likely built by the gentle accretion of ring material in a quiescent environment. A low bulk density for Arrokoth may point towards a similar gentle formation early in the solar system's history, consistent with the low velocity cloud collapse hypothesis supported on other grounds [1, 3].

Future telescopic surveys of small KBO binaries and missions to KBOs and other "pristine" worlds (e.g., long-period comets, centaurs, etc.) may be able to test this hypothesis by directly measuring the densities of these small worlds.

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References: [1] Stern, S. A. et al. (2019) *Science*, 364, eaaw9771. [2] Spencer, J. R. et al. (2020) *Science*, in review. [3] McKinnon, W. B. et al. (2020) *Science*, in review. [4] Grundy, W. M. et al. (2020) *Science*, in review. [5] Porter, S. B. et al. (2019) *EPSC-DPS*, 311 [6] Beyer, R. A. et al. (2019) *EPSC-DPS*, 849. [7] Bierson, C. J. et al. (2019) *EPSC-DPS*, 875. [8] Schenk, P. M. et al. (2019) *EPSC-DPS*, 1140. [9] Werner, R. A. (1994) *CeMDA*, 59, 253–278. [10] Werner, R. A. and Scheeres, D. J. (1997) *CeMDA*, 65, 313–344. [11] Scheeres, D. J. (2012) Orbital Motion in Strongly Perturbed Environments, *Springer-Praxis*, 1–390. [12] Scheeres, D. J. et al. (2016) *Icarus*, 276, 116–140. [13] Scheeres, D. J. et al. (2019) *Nature Astronomy*, 3, 352–361. [14] Richardson, J. E., and Bowling, T. J (2014) *Icarus*, 234, 53–65. [15] Richardson, J. E. et al. (2019) *Icarus*, 329, 207–221. [16] Jorda, L. et al. (2016) *Icarus*, 277, 257–278. [17] Buratti, B. J. et al. (2019) *Science*, eaat2349.

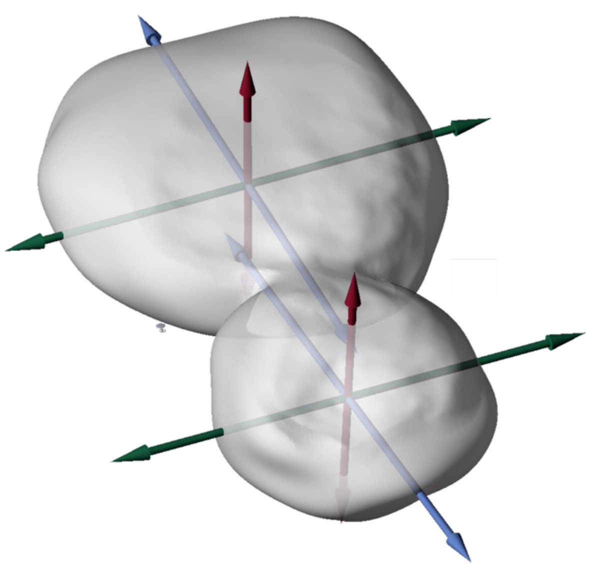

Figure 1 | Principal axes of Arrokoth. *Oblique view of a semi-transparent Arrokoth. The blue, green, and red vectors correspond to the minimum, intermediate, and maximum principal axes of inertia of each lobe, respectively. The vectors originate from the center of mass of each lobe.*