THE POLES AND SHAPES OF SEVEN KUIPER BELT OBJECTS AS MEASURED FROM NEW HORIZONS.
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Immediately after NASA's *New Horizons* spacecraft flew past Pluto in July 2015, it began to explore smaller Kuiper Belt Objects (KBOs) with remote sensing observations as they passed by in the distance. From 2015-2021 *New Horizons* imaged 32 different KBOs with its LOng Range Reconnaissance Imager (LORRI) camera, in addition to the cold classical KBO (486958) Arrokoth at close range (< 3600 km) on January 1, 2019. Many of these observations of KBOs by *New Horizons* were at ranges larger than 0.1 au and are primarily useful as photometric observations at unique viewing geometries impossible from the Earth, with phase angles $\geq 2°$. Here we present rotation rates, rotational poles, and preliminary shapes for seven of these targets that were observed in 2015-2019. All of these objects were observed on at least three different Sun-target-observer angles, and for at least one full rotational period during most of those epochs. We used the DAMIT lightcurve inversion code to produce fits and uncertainties for the poles and rotational periods that produced the optimal fits to the lightcurve. These pole solutions are generally degenerate between prograde and retrograde solutions, but they allow in either case for the approximate shape of the KBO to be estimated. Several objects appear to be flattened, and thus may have a similar appearance to either one or both of the lobes of Arrokoth. This conclusion implies that Arrokoth's shape is not unique, but rather it represents a typical end state for planetesimal formation, which places an important constraint on the formation of planetesimals throughout the Solar System.

One limitation on studying KBOs from the Earth and Earth-orbit is that the phase angle of a KBO reaches at maximum $\sim 2°$, and the geometry of a KBO changes slowly since their orbits are on order ≥ 200 years. One way to get around the geometric constraints of Earth's orbit is to send a spacecraft, like *New Horizons*, through the Kuiper Belt enabling observations at phase angles as high as 150°[1]. Studies of asteroid lightcurves demonstrate that the amplitude of elongated objects increases at higher phase angles [e.g. 2], whereas the amplitude remains the same for spherically shaped objects. Therefore, observations of KBOs by *New Horizons* were designed to obtain photometry of the selected objects at at least three different phase angles spanning as wide a range as feasible in order to sample the phase space of potential physical situations [3, 1, 4]. Here we present the results from seven objects using the DAMIT lightcure inversion code developed by [5], as fit to photometric observations obtained from the *New Horizons* spacecraft. The seven objects that we selected were Arawn (3:2 Resonant), 2011 HF_{103} (Cold Classical), 2011 HK_{103} (Hot Classical), 2011 HZ_{102} (Cold Classical), 2011 JX_{31} (Cold Classical), 2012 HE_{85} (Cold Classical), and 2014 PN_{70} (Cold Classical). These objects have estimated absolute magnitudes ranging from 7.6 to 10, corresponding to approximate sizes from 78-500 km [6], though those estimates are based on assuming perfectly spherical shapes. These KBOs were selected because that had a large amount of observations already downlinked from the *New Horizons* spacecraft; this technique can be applies in the future to additional KBOs observed by *New Horizons* after 2020. We will present our best-fit rotational periods for the seven objects, many of which have sufficiently fast rotational periods that they would be hard to recover from Earth-based observatories. We then present our best rotational pole solutions for each of the seven objects with uncertainties, showing that they are all at curiously high obliquities to their heliocentric orbits. Finally, we present our preliminary results on the shapes of these objects, showing that some of the objects appear to be sufficiently elongated that they are likely to be contact binaries; this result is shown in Figure 1.

We used high-phase photometric observations by the LORRI camera on *New Horizons* to model the poles and shapes of seven KBOs, the first such analysis possible for KBOs. We found that all seven KBOs have rotational poles that are at very high obliquities to their orbit poles. We also found that three of the seven KBOs have shape solutions that are sufficiently elongated and flattened that they are likely to contact binaries. We estimate that 40-70% of KBOs which are not separated binaries are in fact contact binaries, though this is masked in Earth-based photometry dues to their highly-inclined rotational poles. We propose that these contact binaries were formed in a similar way to Arrokoth, and that Arrokoth may represent a common end state for KBO evolution. This work is an initial analysis of the fascinating and unique *New Horizons* KBO lightcurve dataset, and further analysis with improved shape modeling methods and improved estimations of rotational periods from Earth-base photometry will produce even more intriguing results in the future.

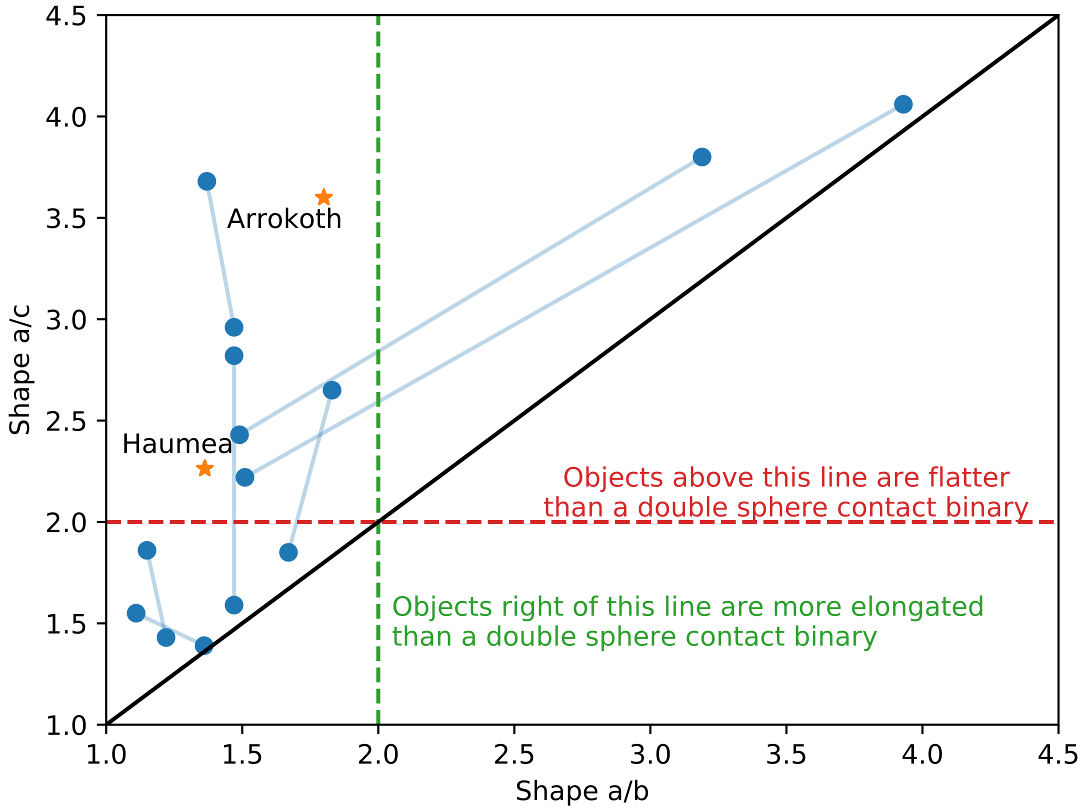

Figure 1: Shapes of KBOs from New Horizons LORRI photometery. "a/b" shows the ratio of the longest equatorial axis to shortest equatorial axis, the elongation. "a/c" shows the ratio of the longest axis to the shortest axis, the flattening. A contact binary consisting of two perfectly spherical lobes of equal volume would have a/b = a/c = 2. The 14 blue points correspond to the two best shape solutions for seven KBOs observed by LORRI in 2016-2020, with lines connecting the two solutions. The shape ratios of Haumea [7] and Arrokoth [8] are shown for comparison. Most of our solutions are considerably flattened, but only two (the retrograde solution for 2011 HF_{103} and the prograde solution for Arawn) are more elongated than a perfect sphere contact binary; both objects also have less elongated solutions.

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