A CONTACT BINARY IN THE KUIPER BELT: THE SHAPE AND POLE OF (486958) 2014 MU69.

S. B. Porter[1], C. J. Bierson[2], O. Umurhan[3], R. A. Beyer[3,4], T. R. Lauer[5], M. W. Buie[1], A. H. Parker[1], M. Kinczyk[6], K. Runyon[7], W. M. Grundy[8], J.J. Kavelaars[9,10], A. M. Zangari[1], M. R. El-Maarry[11], D. T. Britt[12], J. M. Moore[3], A. Verbiscer[13], J. W. Parker[1], C. B. Olkin[1], H. A. Weaver[7], J. R. Spencer[1], S. A. Stern[1], and the New Horizons Geology, Geophysics, and Imaging (GGI) Team. [1]Southwest Research Institute, Boulder, CO (porter@boulder.swri.edu), [2]University of California, Santa Cruz, CA, [3]NASA Ames Research Center, Moffett Field, CA, [4]SETI Institute, Mountain View, CA, [5]National Optical Astronomy Observatory, Tucson, AZ, [6]North Carolina State University, Raleigh, NC, [7]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [8]Lowell Observatory, Flagstaff, AZ, [9]National Research Council of Canada, Victoria BC, [10]University of Victoria, Victoria, BC, [11]Birkbeck, University of London, London, UK, [12]University of Central Florida, Orlando, FL, [13]University of Virginia, Charlottesville, VA.

Background: On January 1, 2019, NASA's *New Horizons* spacecraft encountered (486958) 2014 MU69 (unofficially nicknamed "Ultima Thule"), a cold classical Kuiper Belt Object (KBO). This was the first time that a spacecraft has observed a cold classical KBO up close, and is the most distant object ever to have been targeted by a spacecraft flyby (see abstract by Stern et al.). The cold classical belt is a collection of low-inclination, low-eccentricity objects between approximately 40 and 45 AU from the Sun, and is thought to be the part of the solar system that was least modified by giant planet migration [1]. MU69 was therefore expected to have a mostly-primordial shape that was not heavily-modified by impacts [2]. Many cold classical KBOs show significant photometric variation with periods between 5 and 40 hours [3], though most known rotation rates were for much larger objects. MU69 was thus expected to have to have an irregular shape, and a similar rotational rate to the larger objects with lightcurves visible to ground-based telescopes.

Shape from Occultation Profile: In the lead-up to the flyby with *New Horizons*, MU69 was observed with multiple stellar occultations; see abstract by Buie et al. for details. The most successful of these for probing the shape of MU69 was on July 17, 2017, in and around Comodoro Rivadavia, Argentina. Five chords were successfully obtained on the object then, showing a profile that seemed to be well-fit by two overlapping circles of radius 7.5 and 9 km (see Fig 1). This implied three possibilities: 1) a close binary pair serendipitously in a mutual event, 2) a contact binary viewed not-quite pole-on, or 3) a bent-irregular shape, similar to the near-Earth asteroid (25143) Itokawa. In addition, the occultation results from the SOFIA Observatory in July 2017 and from Senegal in August 2018 seemed to be more consistent with a single elongated object than a non-contact binary. The similarity of the actual shape to the occultation profile shows how powerful this technique can be, and should serve as encouragement for future KBO occultations.

Shape and Rotation from Photometry: In an effort to determine the rotation rate of MU69, the *Hubble Space Telescope* (HST) observed the object in 24 orbits over 9 days in the summer of 2017. Despite this wealth of data, no obvious periodicity could be seen in the photometric measurements of these observations; see [4] for more discussion of this. *New Horizons* obtained optical navigation and satellite/dust search images of MU69 starting in August 2018, typically with a cadence of 24 hours. Puzzlingly, no obvious periodicity was seen in this photometry, either. We now know that this was an effect of MU69's high obliquity; see abstracts by Zangari et al. and Showalter et al. for more on the implications of this.

Shape from Resolved Images: The shape of MU69 was finally revealed when the first close-approach images (from the "CA01" sequence) were downlinked immediately after flyby. These showed a double-lobed body formed from two nearly-spherical lobes, with apparent radii of 7 and 10 km, connected by a thin "neck". For the purposes of discussion, the New Horizons team informally calls the larger lobe "Ultima", and the smaller lobe "Thule". To minimize confusion, we refer to the full object as "MU69" and the lobes as their informal names (see Moore et al. abstract). This confirmed that the shape seen in the stellar occultations was in fact a contact binary. Images from the CA04 sequence that were dowlinked right afterwards show the same shape in more detail, but with a small amount of rotation. In CA04, the smaller lobe Thule is clearly in front of the larger lobe Ultima. For both lobes, the deviations from spheres is less than 2 km; see abstract by Bierson et al. for more about fitting the limb topography of MU69.

To start the shape-fitting process, we constructed a series of clay models, first from the occultation profile, and then from the resolved images (see abstract by Kinczyk et al.). These models were digitally scanned, and then converted to Wavefront OBJ format 3D models (see abstract by Robbins et al.). We used these scanned models to forward-model the orientation of MU69 in the LORRI images. The forward-model uses OpenGL to render a pixel-perfect version of each image, convolves it with the point-spread function (PSF) of LORRI, and compares the result with the image. This technique was developed to fit the shapes and

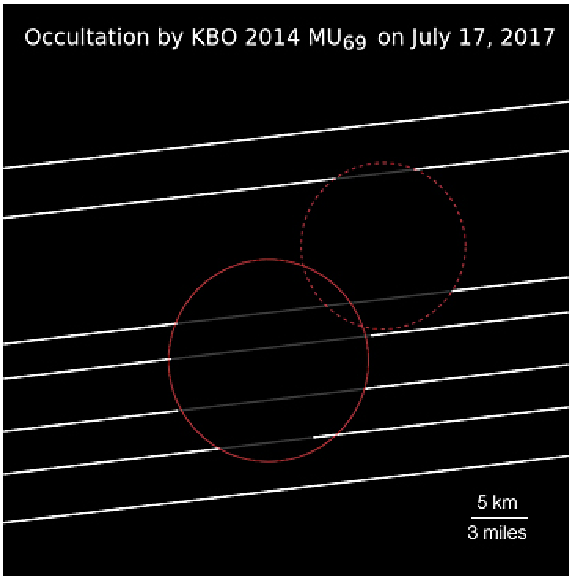

Figure 1: Occultation profile of 2014 MU69 from the July 17, 2017 stellar occultation from Comodoro Rivadavia, Argentina. This successfully showed the contact-binary shape of MU69. Using the pole solution below, MU69 was viewed at a latitude of -76°.

poles of the small satellites of Pluto. Here we held the shape model constant, and used the model to fit the pole, but future work will allow the simultaneous fitting of the pole and shape, allowing us to map any degeneracies between the two.

Rotation and Pole from Resolved Images: In addition to the close-approach images CA01 and CA04, *New Horizons* also downlinked a subset of images obtained in the last two days before the flyby. These images show MU69 as barely-resolved, but clearly elongated. In some of later images of this sequence, it is clear which end is Ultima and which is Thule, helping to break the degeneracy. By combining these barely-resolved images with the well-resolved close-approach images, we were able to fit an approximate rotational period of 15 hours. This period is typical for cold classical KBOs, which can range from 5 and 40 hours [3]. In addition, we were able to fit a rough rotational pole for the body as: RA = 300°, Dec = -21°. This is approximately 23° from the approach direction, helping to explain the low lightcurve amplitude. This pole solution is 92° from the orbit pole. This may limit the number of possible formation scenarios, as such a high obliquity may imply significant inclination evolution prior to the merger of the two lobes. However, this is a very preliminary pole solution, and may be superseded as more and better images are downlinked from the *New Horizons* spacecraft.

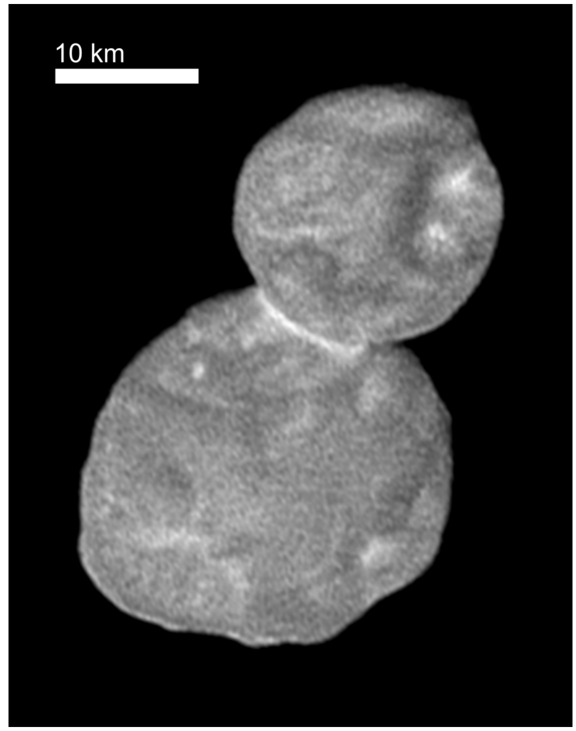

Figure 2: The shape of 2014 MU69 from the CA04 close-approach image sequence. This image has a native resolution of 134 m/pixel, and was deconvolved to enhance detail.

Density: While we do not know the mass, and therefore density, of the lobes, we can place some restrictions on them based on the shape and rotation. Under the assumption that the lobes are in contact and not in a free orbit around a common center of mass we place a lower limit on the density of the two lobes of 0.2 g/cm^3. As we are able to improve the reconstructed trajectory of the New Horizons spacecraft, we will attempt to measure to relative densities of the lobes based on their astrometric offsets from the predicted center-of-mass.

Prospectus: This abstract is being written using the few images that were downlinked immediately after the MU69 flyby. The downlinking of high-resolution images will resume in February 2019, and these images will provide substantially more information on the shape and orientation of MU69. In addition, the rotational coverage sequence that was obtained by the spacecraft a day before flyby will better help to constrain the pole and rotational rate of MU69, as the high-resolution images were taken over a very short period of time.

References: [1] J.-M. Petit et al. (2011) AJ, 142, 4. [2] S. Greenstreet et al. (2019) Submitted to ApJ Letters. [3] A. Thirouin et al. (2010) A&A, 522, A93. [4] S. Benecchi et al. (2019) Submitted to Icarus.