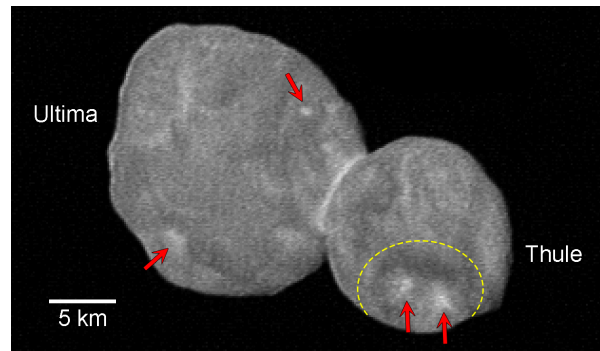


**CRATER MORPHOLOGY ON 2014 MU<sub>69</sub> – PREDICTIONS FOR NEW HORIZONS HIGH RESOLUTION IMAGING** V. J. Bray<sup>1</sup>, O. L. White<sup>2</sup>, K. N. Singer<sup>3</sup>, W. B. McKinnon<sup>4</sup>, P. M. Schenk<sup>5</sup>, S. J. Robbins<sup>3</sup>, J. M. Moore<sup>6</sup>, R. D. Dhirga<sup>7</sup>, J. R. Spencer<sup>3</sup>, C. B. Olkin<sup>3</sup>, J. W. Parker<sup>3</sup>, S. A. Stern<sup>3</sup>, A. J. Verbiscer<sup>8</sup>, H. A. Weaver<sup>9</sup>, and The New Horizons Geology, Geophysics and Imaging (GGI) Team. <sup>1</sup>Lunar and Planetary Lab., The University of Arizona, Tucson, AZ, 85721. <sup>2</sup>SETI Institute, Mountain View, CA. <sup>3</sup>Southwest Research Inst., Boulder, CO. <sup>4</sup>Washington U. in St. Louis, MO. <sup>5</sup>Lunar and Planetary Inst., Houston, TX. <sup>6</sup>NASA Ames Research Center, Moffett Field, CA. <sup>7</sup>University of Idaho, Perimeter Drive, Moscow, ID. <sup>8</sup>University of Virginia, Charlottesville, VA. <sup>9</sup>JHU Applied Physics Lab., Laurel, MD. ([vjbray@lpl.arizona.edu](mailto:vjbray@lpl.arizona.edu)).

**Introduction:** 2014 MU<sub>69</sub> is a cold classical Kuiper Belt Object (KBO), informally nicknamed “Ultima Thule”, hereafter referred to as “MU<sub>69</sub>”. MU<sub>69</sub> was visited by the New Horizons spacecraft on 1<sup>st</sup> January 2019 [1]. Images reveal a contact binary with a 9.73 km diameter lobe nicknamed ‘Ultima’ and a 7.12 km diameter lobe nicknamed ‘Thule’ [2], probably created as the result of a slow and non-destructive impact of two planetesimals. At the low phase angles (11–13°) and relatively low resolution (140 m/pixel) of these early images, topography on MU<sub>69</sub> is ill defined. High-resolution images (reaching 33 m/pixel) will return slowly over the course of 2019, including a downlink in February, the data from which will be presented at the 50<sup>th</sup> LPSC. No unambiguous impact craters have yet been identified on MU<sub>69</sub>, but some albedo features might yet reveal themselves to be craters and their ejecta in the forthcoming higher resolution imaging. These include high albedo patches up to a few kilometers across that are seen on both lobes, as well as a 7–8 km diameter, roughly circular feature with a low albedo rim on the Thule lobe (Fig. 1). MU<sub>69</sub> is expected to be cratered, even if only to a modest degree [3]. This abstract discusses the main factors affecting impact crater morphology on a low gravity icy body. The presentation will include images and analysis of any craters detected in the February-downlinked data, or failing that, a fuller discussion of the striking implications of a total absence of resolved craters on the encounter side of MU<sub>69</sub>.

**Target Conditions and the effect of low gravity on crater morphology:** Kuiper Belt Objects such as MU<sub>69</sub> are assumed to be composed predominantly of H<sub>2</sub>O ice, silicates, organic matter, and other non-H<sub>2</sub>O ices. This is based on density estimates of 0.5 – 1 g cm<sup>-3</sup> [e.g., 2] the dimensions of MU<sub>69</sub> are now available from New Horizons [2, 4] and a conveniently circular shape to the two lobes allows for a volume estimate. Assuming a 1 g cm<sup>-3</sup> average density, this suggests a gravity of ~ 0.003 m s<sup>-2</sup>. The surface gravity of a planetary body affects crater morphology in (at least) two important ways: (1) the crater diameter at which rim terraces and/or central peaks form is inversely proportional to gravity [e.g. 5], and (2) the higher the gravity, the more readily the transient crater



**Figure 1.** MU<sub>69</sub> albedo features potentially of impact origin as seen in the CA04 LORRI observation (140 m/pixel), including relatively bright circular patches up to a few km across (red arrows) and a larger circular feature with a relatively dark rim (yellow ellipse). Phase angle is 12.9 degrees.

collapses, leading to differences in crater morphology. With a surface gravity of only 0.003 m s<sup>-2</sup>, the simple-complex transition diameter for MU<sub>69</sub> should be between 60 and 70 km, i.e. twice as large as the longest dimension of MU<sub>69</sub>, so only simple morphologies are expected. Additionally, when considering the effect of gravity alone, steep wall slopes could be stable due to the effect of low gravity. However, material strength considerations and the very low impact velocities would counteract this effect. It is possible that central structures and rim complexities might be present, but these would be the result of target layering [cf. 6] and/or low-velocity complications.

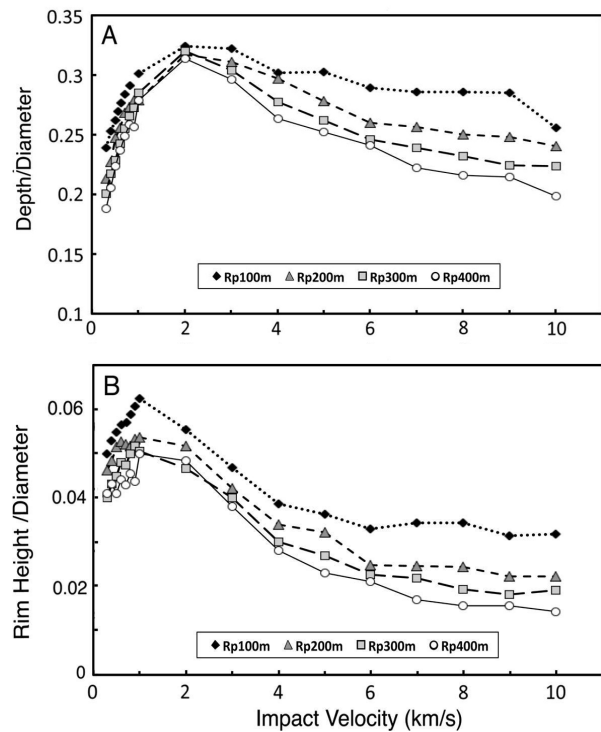
**Impactor properties and the effect of low impact velocity on crater morphology:** The most likely impactors at MU<sub>69</sub> are other KBOs [3]. These can be subdivided into subpopulations based on their solar-distance, resonances, etc. The most likely impactor type would be another main belt ‘cold classical’. Greenstreet et al., [3] consider the range of impactor velocities at MU<sub>69</sub> and predict that impacts into the body will be predominantly sub-sonic: ~ 300 m/s, with a maximum system impact velocity likely to be below 4 km/s. Pluto and Charon are subject to average impact velocities of 2 km/s. Although this velocity is low compared to most planetary bodies under study, obser-

variations [7] and modeling [8] do not suggest any significant shallowing of the crater profile until crater velocities drop below  $\sim 1$ -2 km/s (Fig. 2). A better comparison for what to expect of low velocity impacts is to consider the secondary crater population on icy bodies.

Secondary craters tend to be shallower than primaries due to their lower impact velocity [e.g., 9]. As this is true across multiple bodies of our solar system, we expect craters formed on MU<sub>69</sub> to be shallower than those expected on other small icy bodies that experience higher impact velocities. This could be due to less effective transient crater formation at low impact velocities, which will produce a shallower crater prior to any additional rim collapse. The low gravity on MU<sub>69</sub> is not expected to facilitate significant collapse of this transient crater, compared to the modification that might be expected on higher gravity bodies.

Low velocity impact theory suggests that preservation of the projectile might be possible at very low impact velocities [e.g., 10]. However, observations of secondary cratering on the Moon [9] have not located any preserved projectiles associated with estimated impact velocities down to 50 m/s. Potential impactor preservation at low impact velocities [e.g. 11] might result in albedo differences at the crater center that could be used to discern compositional differences between the impactor and the target. If albedo differences are seen at the centers of craters, and do not appear to be due to post-impact sedimentation, then we are more likely seeing impactor preservation than impact melt – a usual cause for albedo differences at the crater centers [e.g., 12] – because low velocity impacts are less likely to cause melting of the target [e.g., 13]. The highest velocity impacts into MU<sub>69</sub>, combined with the effect of closing pore space [cf. 13], could produce some melt products, although the outcome of this is not expected to be macroscopic. Morphologies associated with melt (water in this case), such as small scale pitting seen in martian craters [14], and melt flows, streaks and ejecta ‘streamers’ [e.g., 15], are therefore not expected.

The amount and range of any ejecta will be affected by both the expected low velocity impacts and the low gravity of MU<sub>69</sub>, although gravity is expected to be the dominant factor of the two. A range of ejecta velocities is expected, with the majority of ejecta being likely to attain velocities in excess of MU<sub>69</sub>’s escape velocity ( $\sim 10$  m/s for a mean density of  $0.5 - 1 \text{ g cm}^{-3}$ ). Ejecta retention is expected to be limited to close-rim material, and will likely not include rays or secondary cratering. Ejecta exchange between the lobes of MU<sub>69</sub> is possible if the ejection angles are fortuitous. This could lead to secondary impacts occurring within the system, but they would not be easily related back to their primary crater.



**Figure 2:** Pluto impact simulation results from [8], showing the decrease in relative crater depth and rim height for different impact velocities. The results include the impact of 100-400 m radius projectiles (Rp = 100-400 m), and assume a solid ice target and projectile, and Pluto gravity. Rim height and crater depth both show a marked decrease when impact velocity drops below  $\sim 1$ -2 km/s.

**REFERENCES:** [1] Stern et al. (2019) LPSC 50, Abstract. [2] Moore et al., (2019) LPSC 50, Abstract. [3] Greenstreet et al., (2019) ApJ Letters, in review. [4] Bierson et al., (2019) LPSC 50 Abstract. [5] Schenk et al. (2004), in Jupiter: The Planet, Satellites, and Magnetosphere, Cambridge Univ. Press, 427-456. [6] Quaide & Oberbeck (1968), JGR planets 73(16):5247-5270. [7] Schenk et al. (2018) Icarus 315:124-145. [8] Bray & Schenk (2015) *Icarus* 246, 156-164. [9] Melosh, 1979 ‘Impact Cratering’. [10] French (1998), Traces of Catastrophe and references therein. [11] Daly & Schultz (2018), MAPs 53(7):1364-1390. [12] Plescia & Cintala (2012) JGR Planets 117(E12). [13] Wunnemann et al., (2008), EPSL 269(3):530-539. [14] Tornabene et al. 2012, *Icarus* 220(2):348-368. [15] Bray et al., 2018, *Icarus* 301: 26-36.