THE GEOLOGY OF 2014 MU_{69} ("ULTIMA THULE"): INITIAL RESULTS FROM THE *NEW HORIZONS* ENCOUNTER.

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Introduction: The *New Horizons* encounter with the cold classical Kuiper Belt object (KBO) 2014 MU_{69} (informally named "Ultima Thule") occurred on 1 January 2019. This was the first time a spacecraft has ever closely observed one of the free-orbiting small denizens of the Kuiper Belt, which was revealed to be a bi-lobate contact binary [1]. Here we review our initial geological analysis of this object, based on intensive work in the first days after post-encounter receipt of data, which is also the time of this abstract's submission. Considerable amounts of additional data will be downlinked by the time of the 2019 LPSC meeting in March. Therefore many new, quite substantial results not available at the time of this abstract submission will be presented in the actual review talk.

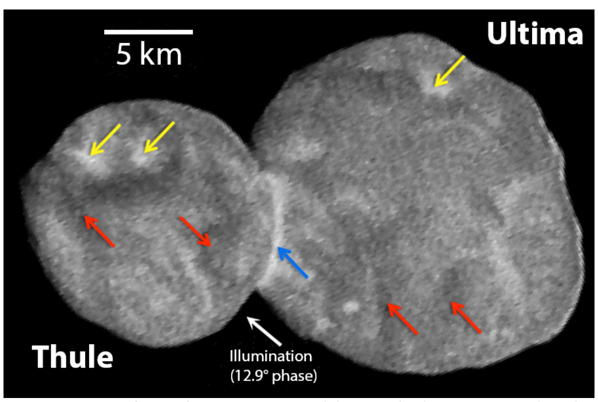

Fig. 1. Surface features on Ultima Thule as seen in the CA04 LORRI observation (140 m/pixel), including relatively bright circular patches a few km across (yellow arrows), relatively dark regions up to several km wide (red arrows), and a bright, cylindrically symmetric neck (blue arrow).

Initial Observations: MU69's two lobes have been informally designated "Ultima" and "Thule" by the *New Horizons* team (Fig. 1). Ultima and Thule have best-fit measured radii of 9.73±0.02 and 7.12±0.06 km, respectively, as seen in projection [2]. In the two observations on the ground at the time of writing, Ultima Thule has a mottled appearance, implying surface complexity. These two observations were acquired at ~300 m/pixel and ~140 m/pixel, both at a lighting phase of ~12° (i.e. the Sun is almost directly behind the spacecraft). Both lobes are very similar in brightness [3], color [4], and composition [5].

Discernible features include quasi-circular bright patches (Fig. 1, yellow arrows) up to a few km across and generally elongate or curvilinear darker regions (red arrows) up to several km wide. The "neck" where Ultima and Thule are joined (Fig. 1, blue arrow) is relatively bright and may represent accumulated fine-grained material, or perhaps material of a different composition, or a combination of both. Preliminary modeling [6] indicates that the regions on both lobes around the "neck" correspond to the steepest slopes on Ultima Thule.

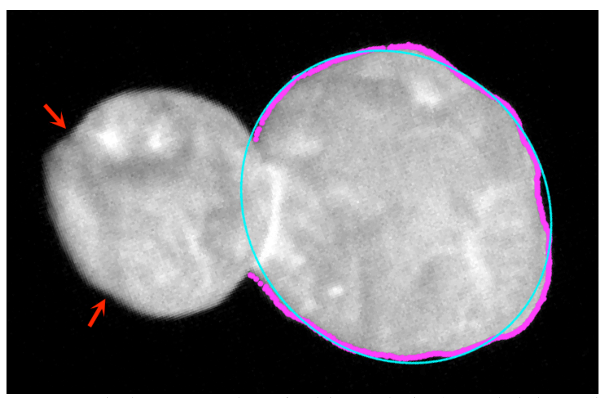

Fig. 2. Limb topography of Ultima Thule (on a brightened version of the image in Fig. 1). The best-fit ellipse to Ultima's shape (in blue) is subtracted from the mapped limb [2] (pink dots) to derive the limb topography. Red arrows indicate "divots" on the limb of Thule.

No impact craters have definitely been resolved yet, but it would be a little surprising if unambiguous examples are not seen in the better illuminated and substantially higher resolution images residing in the spacecraft's memory at the time of this writing (craters *are* seen on other bodies at similar resolutions and illumination [7]). Nevertheless, impact craters may be substantially less common [8], and have more unusual morphologies [9] on Ultima Thule than on the small objects we have explored closer to the Sun. The apparent relative paucity of small objects in the region of Ultima Thule's orbit might result in cumulative crater spatial densities that are low, despite the great age of the object [8, 9]. Low impact velocities combined with low densities in both the target and the impactor might exacerbate this, as low velocity encounters can be more accretional than erosive [9, 10], or these events may at least produce ejecta that remains gravitationally bound and re-accretes on the main body as a mantle. Such a mantle can modify or obscure existing craters, altering apparent crater density. Additionally, if a substantial mantle forms, it might become mobile and be transported across large portions of the body's surface by the seismic energy of later impacts, akin to what is observed on Saturn's moon Helene [11]. Also, if there is a mantle, it might be quite dissipative, which has implications for the tidal evolution of the Ultima Thule binary [12].

Hills and ridges may be present on the surface but have yet to be unambiguously resolved at the time of writing. Weak stereo convergence between the two available observations (see Fig. in [13]) seems to suggest that there may be "hill-like" regions of broad positive relief. Ultima limb topography was extracted by removing a best-fit ellipse (Fig. 2, in blue) from the mapped limb (Fig. 2, in pink). The result indicates a topographic amplitude of ~1 km. Red arrows (Fig. 2) point to apparent "divots" on either side of Thule. The divots appear to be connected by a dark, elongated marking that might be a change in local slope. The accumulation by accretion of last few components within the original "swarm" from which Ultima Thule coalesced may have involved encounters on scales of 1 m s^{-1} [10]. The expression of these final components might express themselves as "hills" on the two remaining lobes. Such a putative hill can be seen around the 4 o'clock position on Ultima in Figs. 1 & 2.

Sublimation-modified landforms, as are commonly seen on comets and a number of other Solar System objects (including Pluto), could have developed on Ultima Thule even if it has never spent any time closer to the Sun than theory suggests for cold classical KBOs [9]. The volatiles most able to sublimate and form erosional landforms would be surface exposures of N_2 and CO. If exposed at the surface, CH_4 will also sublimate, though much more slowly than N_2 and CO, which might even result in landforms mimicking aeolian bedforms [14]. The loss of these volatiles, if present in sufficient quantities and concentrations and susceptible to exposure at the surface, might form distinctive and diagnostic scarps, pits and perhaps lags [e.g., 9, 15, 16]. Sublimation erosion may be focused on accreted material which would be more likely to expose highly volatile ices during the collision process. There could also be local cold traps for volatiles, such as at the neck.

Tectonic features might be reasonably anticipated on Ultima Thule [9]. Many small objects exhibit them, usually in the form of parallel scarps, troughs or coalescing strings of pits. On objects like the martian moon Phobos, these features are thought to be the consequence of impact-induced seismic fracturing of the interior or tides. Ultima Thule is undoubtedly porous, and any long-term radiogenic heating could have led to mild internal compaction and thus some surface compression. Given that Ultima and Thule have converged into contact, the presence, configuration, or absence, of deformation on their surfaces will be very informative. For instance, the appearance of such features on Ultima and Thule would provide insight into the interior strength, coherence, as well as the relative encounter velocities of the final accreting components.

The overall bi-lobate morphology also provides insight into the life cycle of comets. In the inner solar system comets come in two forms, bi-lobate and roughly spherical. The accretional process of forming bi-lobate objects like Ultima Thule may require the ejection of multiple smaller spherical objects [17]. The end result of this process appears to be two morphological populations of comets, one roughly bi-lobate (e.g., 67P/C-G) like Ultima Thule, and the other roughly spherical (e.g., 81P/Wild 2) corresponding to the ejected objects.

Concluding Thought: *New Horizons* has, with the encounter of Ultima Thule, become a time machine, taking us back to almost the very beginning of the solar system, to a place where we can observe the most primordial still-extant building blocks of our world and the worlds around us.

References: [1] Stern, S.A. et al. (2019) *LPSC 50.* [2] Bierson, C.J., et al. (2019) *LPSC 50.* [3] Hofgartner, J.D. et al. (2019) *LPSC 50.* [4] Howett, C., et al. (2019) *LPSC 50.* [5] Grundy, W., et al. (2019) *LPSC 50.* [6] Keane, J.T., et al. (2019) *LPSC 50.* [7] Singer, K.N., et al. (2019) *LPSC 50.* [8] Greenstreet, S., et al. (2018) *Ap J Lett.*, sub. [9] Moore, J.M., et al. (2018) *GRL* 2018GL078996. [10] Nesvorny, D., et al. (2010) *AJ* 140, 785. [11] Umurhan, O.M., et al. (2015) *LPSC 46,* #2400. [12] Nimmo, F. and Matsuyama, I. (2019) *LPSC 50.* [13] Schenk, P.M, et al. (2019) *LPSC 50.* [14] Runyon, K.D., et al. (2019) *LPSC 50.* [15] Spencer, J.R. (1987) *Icarus* 69, 297. [16] Moore, J.M., et al (1999) *Icarus* 140, 294. [17] Umurhan, O.M., et al. (2019) *LPSC 50.*