IMPACT CRATERS ON 2014 MU69: IMPLICATIONS FOR THE GEOLOGIC HISTORY OF MU69 AND KUIPER BELT POPULATION SIZE-FREQUENCY DISTRIBUTIONS. K. N. Singer[1], W. B. McKinnon[2], J. R. Spencer[1], H. A. Weaver[3], T. R. Lauer[4], J. M. Moore[5], S. Greenstreet[6], B. Gladman[7], J. J. Kavelaars[8], P. M. Schenk[9], V. J. Bray[10], S. J. Robbins[1], O. L. White[11], S. A. Stern[1], C. M. Lisse[3], R. D. Dhingra[12], D. T. Britt[13], R. A. Beyer[11], O. M. Umurhan[5], W. M. Grundy[14], L. A. Young[1], C. B. Olkin[1], J. W. Parker[1], A. J. Verbiscer[15], The New Horizons Geology, Geophysics and Imaging Science Theme Team, The New Horizons Ralph Team and LORRI Teams. [1]Southwest Research Inst., Boulder, CO (ksinger@boulder.swri.edu), [2]Washington U. in St. Louis, [6]B612 Asteroid Inst. and DIRAC Center at U. Washington, [7]U. British Columbia, [8]National Research Council of Canada, [9]Lunar and Planetary Inst., [10]U. Arizona, [6]U. Idaho, [7]North Carolina State U., [5]NASA Ames, [11]SETI, [6]Lowell Observatory, [4]NOAO, [3]JHU Applied Physics Lab, [12]U. Idaho, [13]U. Central Florida, [14]Lowell Observatory, [15]U. Virginia.

Introduction: The craters on (486958) 2014 MU69, or the lack thereof, should provide information on both the evolution of the body itself and the size-distribution of the Kuiper belt object (KBO) impactors that made the craters [1–3]. The sizes, depths, and densities of craters will be measured from medium-to-high resolution New Horizons images [see also 4–6].

Early results: Images from two Long Range Reconnaissance Imager (LORRI; [7]) observations of MU69 (nicknamed “Ultima Thule”) were returned in the few days after closest approach (5:33 UTC January 1) at pixel scales of ~300 m px^{-1} (called CA01) and 140 m px^{-1} (called CA04) (Fig. 1). Both are at low phase angles (~11-13°) and thus the observed brightness variations are likely due to a combination of albedo variation and topographic shading. Approximately 40 and 30 additional images of MU69 were taken for CA01 and CA04, respectively. The signal-to-noise ratio (S/N) of these observations can be improved when the full dataset is received and the images stacked. Other higher resolution and higher phase images were obtained by New Horizons but have not yet been returned. The highest resolution images (~35 m px^{-1} ground scale with 3-4 pixels of smear) and an additional scan at ~140 m px^{-1} were taken at a phase angle of ~32° and will allow better characterization of MU69’s topography [5].

In the low-phase images some features are suggestive of sub-circular depressions. Pluto’s moon Nix, which is similar in size to MU69 (average diameter ~40 km), was imaged at 300 m px^{-1} and at a similar, but slightly lower, phase angle of 9.5° (Fig. 1). This image of Nix displays some typical bright-dark pairs indicative of more symmetrical, circular depressions that are interpreted to be impact craters [8]. The low-phase images of MU69 do not reveal quite the same type of obvious symmetrical features. However, the signal to noise is higher for the Nix image: per pixel

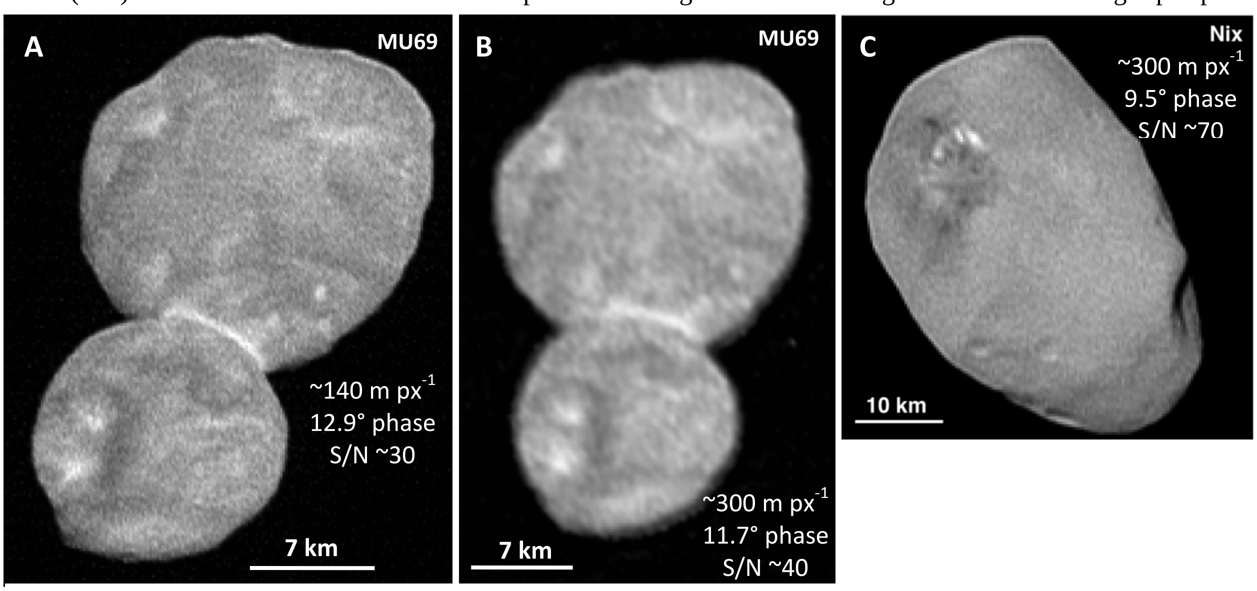

Fig 1. (A) Single image deconvolution of 2014 MU69 (LORRI observation CA04) shown at native pixel scale. Dark and bright variations at this relatively low phase angle could be due to either topography or albedo variation. **(B)** Two image deconvolution of 2014 MU69 (LORRI observation CA01) shown at twice the native pixel scale. **(C)** Single image deconvolution of Nix (LORRI observation N_LEISA_LORRI_BEST [8]) shown at native pixel scale. (Deconvolution courtesy T. Lauer.)

S/N of ~70 compared to ~30–40 for the MU69 images. Thus subtle shading due to topography at low phase may be washed out in the MU69 images. The impact velocities on Nix are on average higher than at MU69 (~2 km s^{-1} vs. ~300 m s^{-1}), but the Nix image still provides a comparison of how features may appear visually.

It is possible some of the limb topography seen on MU69 is due to impact craters but none are confirmed at this time. The two bright areas on the left side of the small lobe in Fig. 1. may, or may not, be related to impact craters, as they could represent a smaller crater surrounded by a bright ejecta deposit or they could be topographic lows created by impacts that later collected bright material [9]. We emphasize that we do not assume at this time that any of these features are impact craters, and we will conduct further analysis upon receipt of additional images.

Even given the limitations of the available data at the time of writing, it does not appear that MU69 is a heavily cratered body.

Impact conditions on MU69: The proportions of different Kuiper belt sub-populations that impact MU69 are somewhat different than those that impact the Pluto-system [2,10]. The impactors at MU69 are dominantly the main classical belt (~86%), in contrast to the Pluto-system where other plutinos (resonant 3:2 objects) are the largest contribution. The velocity distribution of all impacting populations is given in [2]. The most typical impact velocity is of order 300 m s^{-1}, although impacts may occur at even lower velocities, < 100 m s^{-1}, or as high as 3–4 km s^{-1}. Importantly, the overall density of craters on MU69 is predicted by [2] to be fairly low, because the size-frequency distribution of small Kuiper belt objects that would be impacting MU69 is thought to have a shallow power-law slope [3]. Only 30 craters larger than 200 m in diameter are predicted to form over the entire surface area of MU69 in 4 billion years [2] (a 10 km radius sphere was used in [2]). Heavily cratered surfaces are not expected if this shallow size distribution is applicable to the sub-populations impacting MU69.

The low impact velocities for MU69 are more similar to that of secondary cratering on other worlds, and are well below the typical P-wave sounds speeds in ice [11,12]. It is possible these low velocities could result in atypical crater morphologies [1,2,6]. The low surface gravity on MU69, ~0.003 m s^{-2} for a 1000 kg m^{-3} density body, offsets some of the effect of low impact velocities and yields estimates of cratering efficiency (the ratio of the excavated target mass to the mass of the impactor) of ~20-40 for a regolith-like material [e.g., 13,14]. These are somewhat low values, but similar to, or higher than, those of secondary craters on other worlds [11,14].

Discussion: Craters observed across the surface of MU69 (or the lack thereof) can potentially provide information on the formation of the binary itself and the evolution over time [4,15,16]. How impacts have modified the overall shape of MU69 or the smaller scale topography (e.g., how filled-in or modified the neck region is) will help us constrain how much of a "primordial" shape is preserved from MU69's formation, and what role impacts may have played in the merger and angular momentum evolution of the body. Additionally, craters may reveal subsurface material, providing an opportunity to asses the composition of less-processed material.

The craters on MU69 may not be numerous enough to create a statistically significant size-frequency distribution. The lack of craters in a given size range, however, can still potentially be used to place limits on the impact flux (taking into account any modification by geologic processes). In this talk we will present on the above and compare crater measurements on MU69 to predicted crater densities [2] and craters in the Pluto-system [3].

Craters in the Pluto system revealed a previously-unknown deficit of small KBOs (less than ~1–2 km in diameter) [3], relative to what would be predicted by extrapolated from larger objects observed by telescopic surveys. Objects less than ~1-2 km in diameter are also the sizes primarily impacting MU69. From the initial images, there does not appear to be a large number of craters, which may be consistent with the crater data from the Pluto-system and also indicates a deficit of small KBOs.

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References: [1] Moore J.M. et al. (2018) *GRL, 45*, 8111-8120. [2] Greenstreet S. et al. (2019) *ApJL*, submitted. [3] Singer K.N. et al. (2019) *Science*, doi:10.1126/science.aap8628. [4] Moore J.M. et al. (2019) *LPSC 50*. [5] Schenk P.M. et al. (2019) *LPSC 50*. [6] Bray V.J. et al. (2019) *LPSC 50.* [7] Cheng A.F. et al. (2008) *SSR, 140*, 189-215. [8] Weaver H.A. et al. (2016) *Science, 351*, aae0030. [9] Dhingra R. D. et al. (2019) *LPSC 50.* [10] Greenstreet S. et al. (2015) *Icarus, 258*, 267-288. [11] Singer K.N. et al. (2013) *Icarus*, 226, 865-884. [12] Vogt C. et al. (2008) *J. Acoust. Soc. Am. 124*, 3613–3618. [13] Holsapple, K.A. (1993) *AREPS, 21*, 333-373. [14] Singer K. N. et al. (2019) *JGR*, submitted. [15] Stern S.A. et al. (2019) *LPSC 50.* [16] McKinnon W.B. et al. (2019) *LPSC 50.*