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Impact craters on 2014 MU69: The geologic history of MU69 and Kuiper belt object size-frequency distributions

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Abstract

Impact craters in the Pluto system as observed by New Horizons in July of 2015 revealed a previously-unknown deficit of small Kuiper belt objects (KBOs) less than ~1–2 km in diameter [1]. This deficit is relative to what would be predicted by extrapolated from larger objects observed by telescopic surveys. New Horizons was poised to test this observation 3.5 years later with its next KBO close flyby of the cold classical KBO (486958) 2014 MU69 (nicknamed Ultima Thule). Other KBOs less than ~1–2 km in diameter are also the sizes of objects primarily impacting MU69 [2]. The images returned by New Horizons in early 2019 show MU69 is only modestly cratered, and potential craters on the surface show a shallow size-frequency distribution (SFD) similar to that of crater in on Pluto and Charon [3-5].

1. Images and mapping methods

We examined all images taken on approach to Ultima Thule for possible crater features. The images suitable for viewing potential craters on the surface range in ground scale from 33–300 m px^{-1}. The lighting geometry also varies, as the phase angle is quite low for most of the approach (~11–13°) and thus is not ideal for viewing topographic features (albedo features are emphasized instead). The closest approach image stack (CA06), however, has reasonable resolution and lighting for viewing features over a good portion of MU69 (phase angle of 32°). Even with deconvolution techniques applied to the images, the effective resolution of the CA06 observation is reduced to ~70 m because of smear in one direction during New Horizon's fast flyby (~14 km s^{-1}) of MU69 and the camera point-spread-function.

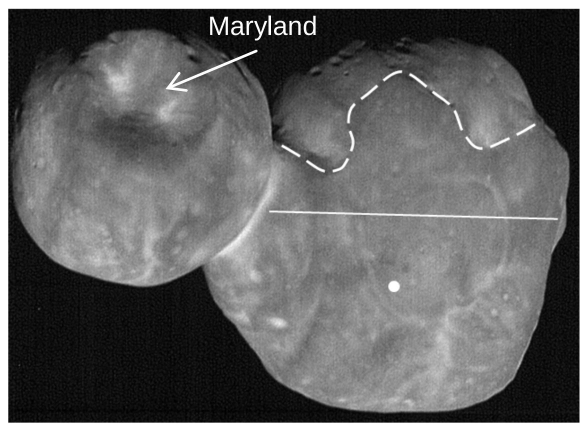

Figure 1: Highest resolution image stack of 2014 MU69 (deconvolved CA06 observation, ground scale ~33 m px^{-1}, effective resolution ~70 m, phase angle 32°). The white dot indicates the ~sub-solar point. The solid white line divides the larger lobe into two halves. The lower half has a higher sun angle (lighting more directly overhead) and more albedo features (bright/dark) can be seen. The upper half has more oblique lighting that is better for viewing topographic features and more depressions can be seen in this area. The white dashed line indicates the lower boundary of one potential geologic unit in an area with favorable lighting that was also used for crater analysis. The depression informally named Maryland is the largest likely impact crater.

The crater-like features on MU69 can be roughly divided into two morphologic categories: (i) circular or sub-circular depressions and (ii) circular or sub-circular bright features. All features were also categorized by how likely a team of mappers considered them to be impact features based on the morphology expected for either fresh or degraded impact craters. The spatial arrangement of the potential craters and their relationship to other geologic features was also accounted for. The bright sub-circular features may be depressions where material collected, as it seems bright material has collected in other topographic lows (e.g., the neck). For a fresh crater formed on a relatively simple surface (e.g., a smooth surface) a crater rim is expected to be close to circular, the rim may be raised above the surrounding terrain depending on the impact conditions, and the shape of the interior of the crater is expected to be bowl-like with a depth-to-diameter ratio typically $\lesssim$ ~0.2.

There is variation in crater formation based on the impactor or target conditions. Most impacts onto MU69 are likely low velocity [2]. The most common primary impact speed onto MU69 is ~300 m s^{-1}. Impact velocities in the few hundred meters per second range are typical of secondary cratering velocities which form craters on the surfaces of both icy and rocky bodies across the solar system [6]. These impacts often still form craters with similar morphological characteristics, although secondary craters are often shallower than the same size primary impact, and may be elongated in the direction radial to the primary crater. We are not suggesting any craters on MU69 are secondary craters, but simply using the analogy to secondary craters to show that 300 m s^{-1} impacts could still create a crater on the surface of MU69. The low and high velocity tails of the impact velocity distribution reach down to a few m s^{-1} and as high as a few km s^{-1} [2]. Craters formed at the very low velocities of a few m s^{-1} may not form a recognizable depression in the surface. The formation of a crater on a slope or modification by later geologic processes (such as mass wasting or a subsequent fault near the crater) may also alter the crater's appearance.

2. Results

Some features on MU69 do have multiple morphologic indicators suggesting they are impact craters and that at least some impactors have high enough velocities to produce typical crater morphologies. Even taking into account all of the caveats mentioned above, the surface appears only modestly cratered. There are regions on MU69 with few-to-no craters, even where the lighting is favorable for recognizing topographic features. The ~7-km-diameter depression on the small lobe (informally called Maryland) is the largest easily observed feature that is likely to be an impact crater, although other topography on the limb of MU69 may be related to similar-scale impacts. The excavation of Maryland also appears to have exposed some brighter subsurface material. Craters intermediate in size between Maryland and ~1 km are not apparent [3].

The possible impact craters under ~1 km in diameter were divided into subgroups based on morphology, likelihood of being a crater, lighting geometry, and also into one possible geologic unit in favorable lighting. All subgroups produced shallow-sloped SFDs (differential power-law slope $\lesssim -2$) similar to those seen on Pluto and Charon for the same size craters (when scaled for gravity and impact velocity) [7]. Whole-sale resurfacing through geologic processes over time is not expected for MU69. Thus many more total craters, and at least some heavily cratered terrains would be predicted if the impactor SFD slope were steeper (an average differential slope closer to -3), as is seen for both the larger craters in the Pluto-system and the observed current population of KBOs under ~100 km in diameter [2, 4]. Both the apparent lack of craters overall, and the shallow SFD slopes, are consistent with a relatively benign collisional environment for MU69 [8].

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