COMPARING (486958) 2014 MU_{69} TO COMETARY NUCLEI: SHAPES AND SURFACES.

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Introduction. On 1 January 2019, NASA's New Horizons mission conducted a close flyby of the cold classical Kuiper Belt Object (KBO) (486958) 2014 MU_{69} (hereafter MU69), nicknamed Ultima Thule [1]. Here we investigate the similarities and differences in the shape and surface morphology of MU69 compared to those of the short period cometary nuclei (also called Jupiter family comets, or JFCs) studied by flyby or rendezvous spacecraft missions.

Dynamical Considerations. By virtue of its small orbital inclination angle (2.45°) and small eccentricity (0.045), MU69 qualifies as a member of the cold classical population of the Kuiper Belt. Unlike the KBOs in orbital resonance with Neptune (e.g., the plutinos in the 3:2 resonance), or the scattered KBOs and hot classicals, whose current orbits are significantly perturbed by gravitational interactions with Neptune, the cold classicals probably formed in place ~4.5 Gy ago near their current heliocentric distances and have been relatively undisturbed dynamically over the age of the solar system. Since MU69 is both dynamically cold and physically small (implying little geological processing), it is likely the most primitive object ever encountered by a spacecraft. Thus, MU69's size, shape, density, rotational state, color, and composition today provide a window into the physical, chemical, and accretional conditions in the outer solar nebula.

The vast majority of the JFCs originally belonged to the scattered KBO population [e.g., 2], which likely formed at heliocentric distances between ~15 and 30 AU and were subsequently pushed out to larger distances by the radial migration of the giant planets [e.g., 3]. Gravitational interactions with Neptune transferred some scattered KBOs to the giant planet region where they become Centaurs. And some of those Centaurs are transferred to the inner solar system where gravitational interactions with Jupiter dominates their subsequent orbital evolution.

JFCs have typically spent ~1000-10,000 years at relatively small heliocentric distances (< 6 AU) and have consequently suffered substantial evolution associated with solar heating, which drives sublimation of their stored volatiles (i.e., condensed ices, or gases trapped within amorphous water ice or clathrates). A key issue is how much the thermal and erosional evolution of JFC nuclei has affected their current physical properties and chemical compositions.

JFC Nuclei Studied by Spacecraft Missions. The JFC nuclei considered here are compared to MU69 in Fig. 1. 9P/Tempel was investigated by the Deep Impact [4] and Stardust-NExT [5] missions, 19P/Borrelly was the main target of the Deep Space 1 mission [6], 67P/Churyumov-Gerasimenko (CG) was orbited by the Rosetta spacecraft [7], Stardust conducted a flyby of 81P/Wild [8], and the DIXI mission conducted a flyby of 103P/Hartley [9].

Comparisons of MU69 and JFC Nuclei. Comparisons of the colors and compositions of JFCs and MU69 are addressed by other New Horizons team papers [10,11]. MU69 shares the "ultra-red" color of other classical KBOs with a spectral reflectivity gradient at optical wavelengths that is ~5-10 times steeper than measured for JFC nuclei. At near-infrared wavelengths (1-2.5 μm), MU69 has a mostly featureless (for the data received so far) but slightly red spectrum that mimics what is seen on the surfaces of many outer solar system objects and is often attributed to tholins (radiation-processed macromolecular organics). JFCs typically display significant outgassing of volatiles, but searches for activity from MU69 have so far been negative [12], possibly due to MU69's large heliocentric distance (43 AU) and perhaps suggesting a lack of hyper-volatile ices (e.g., CH_4, CO, N_2, O_2). The geometric albedo of MU69 is typical of cold classical objects (~20%, [13]) and is ~3-10 times higher than those measured for JFC nuclei (2-6%, [14]). Here we compare the shapes and surfaces of MU69 with the shapes and surfaces of the JFCs studied by spacecraft missions.

MU69 is much larger than the JFC nuclei discussed here (Fig. 1), but that alone doesn't discriminate among various formation scenarios (e.g., collapse due to gravitational instability, such as triggered by the streaming instability or turbulence, vs collisional remnants). MU69 appears to be a contact binary, with the two lobes

having roughly spherical diameters of ~19.5 km and ~14.2 km [15], likely the result of a low velocity merger of two primordial planetesimals [16,17]. Among the JFC nuclei, 19P, 67P, and 103P plausibly have bi-lobate shapes, suggesting a formation process similar to that of MU69. 9P and 81P have distinctly different shapes, suggesting they could be the single, primordial objects that escaped during the process that more commonly produced well-separated or contact binaries in the Kuiper Belt [16].

The highest resolution MU69 images downlinked so far have 140 m/pix and were taken at relatively low phase angles (~11-13°), which makes it difficult to see surface features. Nevertheless, MU69 seems to have significant (factor of ~2) brightness variations across its surface and shows hints of depressions and ridges. Traces of MU69's shape show topographical variations of ~0.5-1 km [15], which are modest for an object this size. There is a bright, thin (possibly unresolved) ring around the boundary between MU69's two lobes, which could be produced by a number of processes (e.g., different-sized grains accumulating at a gravitational low or at the bottom of sloping terrains, material shaded from processing by radiation and/or sunlight, to cite two ideas). Three JFC nuclei have "necks" between putative lobes that may or may not have any relation to MU69's ring. The surfaces of the JFC nuclei display complex features attributable to cometary activity, but analogous features on MU69 would not be resolved in the currently available images. Detailed surface morphology comparisons (e.g., crater densities, sublimation pits, topography, etc.) must await the downlink of higher resolution and higher phase angle images of MU69 over the next few months.

References. [1] Stern S.A.+ (2019) *LPSC 50,* this meeting. [2] Gomes, R.+ (2005) *Nature, 435,* 466. [3] Duncan, M., + (2004) in *Comets II*. [4] A'Hearn, M.F. + (2005), *Science, 310*, 258. [5] Veverka, J. + (2013), *Icarus, 222,* 424. [6] Soderblom, L.A. + (2002) *Science*, *296*, 1087. [7] Thomas, N. + (2015) *Science, 347,* 6220. [8] Brownlee, D.E. + (2004) *Science, 304,* 1764. [9] A'Hearn, M.F. + (2011), *Science*, 332, 1396. [10] Protopapa, S. + (2019) *LPSC 50,* this meeting. [11] Quirico, E. + (2019) *LPSC 50,* this meeting. [12] Gladstone, R.G. + (2019) *LPSC 50,* this meeting. [13] Hofgartner, J.D. + (2019) *LPSC 50,* this meeting. [14] Fernandez, Y.R. + (2016) *AAS meeting #227, id* 141.22. [15] Bierson, C.J. + (2019) *LPSC 50,* this meeting. [16] McKinnon, W.B. + (2019) *LPSC 50,* this meeting. [17] Umurhan, O.M. + (2019) *LPSC 50,* this meeting.

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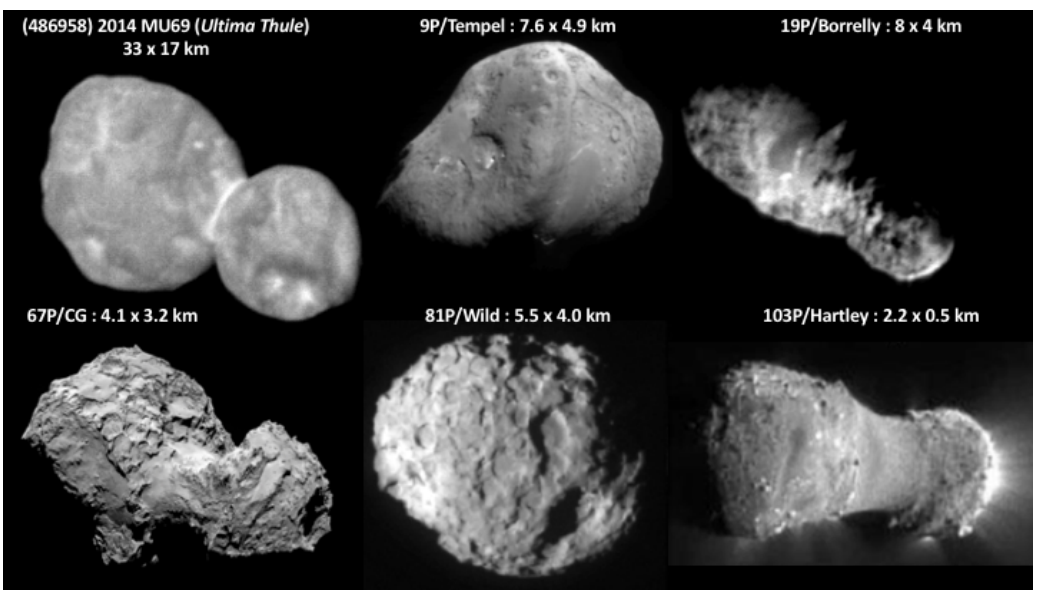

Figure 1: Ultima Thule (UT) is compared to five cometary nuclei visited by spacecraft. Although three of the nuclei show hints of bi-lobate shapes, Ultima Thule is the most obvious example of a contact binary, reflecting its primitive nature. Higher resolution images of UT downlinked by late-February 2019 will enable an even better comparison.