RESEARCH ARTICLE SUMMARY

OUTER SOLAR SYSTEM

Initial results from the New Horizons exploration of 2014 MU₆₉, a small Kuiper Belt object

S. A. Stern* et al.

INTRODUCTION: The Kuiper Belt is a broad, torus-shaped region in the outer Solar System beyond Neptune’s orbit. It contains primordial planetary building blocks and dwarf planets. NASA’s New Horizons spacecraft conducted a flyby of Pluto and its system of moons on 14 July 2015. New Horizons then continued farther into the Kuiper Belt, adjusting its trajectory to fly close to the small Kuiper Belt object (486958) 2014 MU₆₉ (henceforth MU₆₉; also informally known as Ultima Thule). Stellar occultation observations in 2017 showed that MU₆₉ was ~25 to 35 km in diameter, and therefore smaller than the diameter of Pluto (2375 km) by a factor of ~100 and less massive than Pluto by a factor of ~10⁶. MU₆₉ is located about 1.6 billion kilometers farther from the Sun than Pluto, and was at the time of the New Horizons flyby. MU₆₉’s orbit indicates that it is a “cold classical” Kuiper Belt object, thought to be the least dynamically evolved population in the Solar System. A major goal of flying past this target is to investigate accretion processes in the outer Solar System and how those processes led to the formation of the planets.

Because no small Kuiper Belt object had previously been explored by spacecraft, we also sought to provide a close-up look at such a body’s geology and composition, and to search for satellites, rings, and evidence of present or past atmosphere. We report initial scientific results and interpretations from that flyby.

RATIONALE: The New Horizons spacecraft completed its MU₆₉ flyby on 1 January 2019, with a closest approach distance of 3538 km—less than one-third of its closest distance to Pluto. During the high-speed flyby, made at 14.4 km s⁻¹, the spacecraft collected ~50 gigabits of high-resolution imaging, compositional spectroscopy, temperature measurements, and other data on this Kuiper Belt object. We analyzed the initial returned flyby data from the seven scientific instruments carried on the spacecraft: the Ralph multicolor/panchromatic camera and mapping infrared composition spectrometer; the Long Range Reconnaissance Imager (LORRI) long–focal length panchromatic visible imager; the Alice extreme/far ultraviolet mapping spectrograph; the Radio Experiment (REX); the Solar Wind Around Pluto (SWAP) solar wind detector; the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) high-energy charged particle spectrometer; and the Venetia Burney Student Dust Counter (VBSDC), a dust impact detector.

RESULTS: Imaging of MU₆₉ showed it to be a bilobed, contact binary. MU₆₉’s two lobes appear to have formed close to one another, becoming an orbiting pair that subsequently underwent coupled tidal and orbital evolution to merge into the contact binary we observe today. The object rotates on its axis every 15.92 hours; its rotation pole is inclined approximately 98° to the plane of its heliocentric orbit. Its entire surface has a low visible-wavelength reflectivity (albedo) but displays brighter and darker regions across its surface, ranging from 5 to 12% reflectivity. The brightest observed regions are the “neck” of MU₆₉, where the two lobes are joined, and two discrete bright spots inside the largest crater-like feature on the object’s surface. Although MU₆₉’s albedo varies substantially across its surface, it is uniformly red in color, with only minor observed color variations. This coloration likely represents a refractory residue from ices and organic molecules processed by ultraviolet light and cosmic rays. Spectra of the surface revealed tentative absorption band detections due to water ice and methanol. The geology of MU₆₉ consists of numerous distinct units but shows only a small number of craters, providing evidence that there is a deficit of Kuiper Belt objects smaller than ~1 km in diameter, and that there is a comparatively low collision rate in its Kuiper Belt environment compared to what would be expected in a collisional equilibrium population. A three-dimensional shape model derived from the images shows MU₆₉ is not simply elongated but also flattened. The larger lobe was found to be lenticular, with dimensions of approximately 22 × 20 × 7 km (uncertainty <0.6 × 1 × 2 km), whereas the smaller lobe is less lenticular, with dimensions of approximately 14 × 14 × 10 km (uncertainty <0.4 × 0.7 × 3 km). No evidence of satellites, rings, or an extant atmosphere was found around MU₆₉.

CONCLUSION: Both MU₆₉’s binarity and unusual shape may be common among similarly sized Kuiper Belt objects. The observation that its two lobes are discrete, have retained their basic shapes, and do not display prominent deformation or other geological features indicative of an energetic or disruptive collision indicates that MU₆₉ is the product of a gentle merger of two independently formed bodies.

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Initial results from the New Horizons exploration of 2014 MU₆₉, a small Kuiper Belt object

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The Kuiper Belt is a distant region of the outer Solar System. On 1 January 2019, the New Horizons spacecraft flew close to (486958) 2014 MU₆₉, a cold classical Kuiper Belt object approximately 30 kilometers in diameter. Such objects have never been substantially heated through and explored the Pluto dwarf planet system in 2015 (4, 5). The spacecraft has since continued farther to explore Kuiper Belt objects (KBOs) and the Kuiper Belt radiation and dust environment (6).

The target selected for the subsequent New Horizons KBO flyby was (486958) 2014 MU₆₉ (hereafter MU₆₉, also informally referred to as Ultima Thule). This KBO was discovered in 2014 when the Hubble Space Telescope (HST) was being used to conduct a dedicated search for New Horizons KBO flyby targets (7, 8). Before the arrival of New Horizons, the only definitive facts regarding MU₆₉ were its orbit (8), its red color (9), its size of ~30 km (7), and its lack of discrete geological units, and noticeable albedo heterogeneity. However, there is little surface color or compositional heterogeneity. No evidence for satellites, rings or other dust structures, a gas coma, or solar wind interactions was detected. MU₆₉’s origin appears consistent with pebble cloud collapse following a low-velocity merger of its two lobes.

The Kuiper Belt is a torus-shaped ensemble of objects in the outer Solar System beyond the orbit of Neptune, which was discovered in 1992. This is the source region for Jupiter-family comets and contains primordial planetesimals and dwarf planets (e.g., (7)). The 2003 Planetary Decadal Survey ranked exploration of the Kuiper Belt at the top of funding priorities for NASA’s planetary program (2). The resultant NASA mission, New Horizons [e.g., (3)], flew from these encounter observations. MU₆₉ is a bilobed contact binary with a flattened shape, discrete geological units, and noticeable albedo heterogeneity. However, there is little surface color or compositional heterogeneity. No evidence for satellites, rings or other dust structures, a gas coma, or solar wind interactions was detected. MU₆₉’s origin appears consistent with pebble cloud collapse following a low-velocity merger of its two lobes.

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detected variations in its light curve (10) or large, distant satellites. 

MU₆₉'s orbit has a semimajor axis a = 44.6 astronomical units (AU), with eccentricity e = 0.042 and inclination i = 2.45°, making it a member of the cold classical KBO (CCKBO) population (here, cold refers to low dynamical excitation, not surface temperature). CCKBOS are thought to be (i) distant relics formed from the Solar System's original protoplanetary disk and (ii) more or less dynamically undisturbed bodies that therefore formed in situ ~4.5 billion years ago and have since remained at or close to their current, large heliocentric distances (11, 12). Relative to other Kuiper Belt populations, CCKBOS have a more uniformly red color distribution (e.g., (13)), as well as a different size-frequency distribution (i.e., the population of objects as a function of object size) (14) and higher average visible albedos than are typical in the Kuiper Belt [e.g., (15)]. Additionally, many CCKBOS have satellites (16).

Because CCKBOS are dynamically undisturbed from their formation location (or nearly so (12)), they have never been warmed above the ambient, radiative equilibrium temperatures of 30 to 60 K in the Kuiper Belt. MU₆₉'s small equivalent spherical diameter of ~19 km is insufficient to drive internal evolution long after its formation. Therefore, small CCKBOS like MU₆₉ are expected to be primordial planetesimals, preserving information on the physical, chemical, and accretional conditions in the outer solar nebula and the processes of planetesimal formation (e.g., (1, 12)).

New Horizons flew closest to MU₆₉ at 05:33:22.4 ±0.2 s, 1° universal time (UT) on 1 January 2019. The closest approach distance of 3538.5 ± 0.2 (1σ) km was targeted to the celestial north of MU₆₉'s center; its relative speed past MU₆₉ was 14.43 km s⁻¹. The asymptotic approach direction of the trajectory was approximately in the ecliptic plane at an angle of 11.6° from the direction to the Sun. The flyby's observation planning details have been summarized elsewhere (6). This report of initial flyby results is based on the ~10% of all collected flyby data that had been sent to Earth before 1 March 2019; full data transmission is expected to complete in mid-2020.

New Horizons carries a suite of seven scientific instruments (3); all were used in the flyby of MU₆₉. These instruments are (i) Ralph, which consists of the Multispectral Visible Imaging Camera (MVIC), a multicolor/panchromatic mapper, and the Linear Etalon Imaging Spectral Array (LEISA), an infrared (IR) composition mapping spectrometer; (ii) the Long Range Reconnaissance Imager (LORRI), a long-focal length panchromatic visible camera; (iii) the Alice extreme/far ultraviolet mapping spectrophotometer; (iv) a Radio Experiment (REX) to measure surface brightness temperatures and X-band radar reflectivity; (v) the Solar Wind Around Pluto (SWAP) charged-particle solar wind spectrometer; (vi) the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) MeV charged-particle spectrometer; and (vii) the Venetia Burney Student Dust Counter (VBSDC), a dust impact detector.

General properties

MU₆₉ (Fig. 1) has a bilobate shape with two discrete, unevenly sized lobes. This shape demonstrates that it is a contact binary—that is, a pair of formerly separate objects now in physical contact with one another. These two lobes contact at an annular interface with higher than average surface reflectance, which we refer to as MU₆₉'s neck. The larger and smaller lobes of MU₆₉ have been informally designated "Ultima" and "Thule," respectively; formal names will be assigned at a later date.

The bilobate nature of MU₆₉ is reminiscent of known bilobate comets that have been imaged by spacecraft (17–22). However, MU₆₉'s residence in the cold classical Kuiper Belt makes clear that its bilobate shape must be primordial, making MU₆₉ the only unquestionably primordial contact binary so far explored by spacecraft. MU₆₉'s two lobes are discrete, have retained their basic shapes, and do not (at the available resolution) display prominent compression fractures, deformation, or other geological features indicative of an energetic or violent merger. All available evidence indicates that MU₆₉ is instead the product of a gentle collision or merger of two independently formed bodies, possibly contacting one another at (or more slowly than) their mutual gravitational infall speed, which we estimate to be several meters per second (based on plausible densities; see below).

The observed bilobate shape is inconsistent with a recent formation from the collision of two separate, heliocentric CCKBOS because the characteristic relative impact speeds of CCKBOS are currently ~300 m s⁻¹ (23). Such a collision would have heavily deformed or destroyed the two components of the contact binary. We conclude that the lobes instead most likely formed and merged in a gentle dynamical environment, such as in a localized particle cloud collapse early in Solar System history [e.g., (24, 25)], further indicating that MU₆₉ itself is primordial. The similarity in albedos and colors of the two lobes (discussed below) is further evidence for this formation hypothesis.

Images taken during the approach phase show that the rotational period of MU₆₉ is 15.92 ± 0.02 hours; this period is consistent with other CCKBO rotational periods (9, 26, 27). MU₆₉'s rotational pole was found to point at approximately right ascension = 311°, declination = −25°, corresponding to an obliquity of 98° with respect to MU₆₉'s heliocentric orbital plane; that is, MU₆₉ currently rotates almost face-on to the Sun. This pole position, and the fact that the spacecraft approach vector was only ~36° from the direction of the KBO's spin axis, resulted in a light curve of very low amplitude, which was not detected until shortly before the flyby despite many weeks of prior observations from New Horizons. Because asymmetric reradiation (i.e., YORP, or Yarkovsky-O'Keefe-Radzievskii-Paddack) effects are ineffective on bodies the size of MU₆₉ at large distances from the Sun (28, 29), and because (as described below) the visible evidence for impact cratering on MU₆₉ is modest, the spin period and obliquity of MU₆₉ are unlikely to have substantially changed since the binary merger.

We simultaneously fitted the shape of MU₆₉ and its pole position using a forward-modeling process. For each of the early-return LORRI and MVIC images in which MU₆₉ was resolved, this process rendered the shape with the relevant illumination and orientation using the photometric parameters described below; convolved that rendered image with the appropriate point-spread function (for LORRI or MVIC, as appropriate) to simulate the angular resolution and smearing of the real images, and then numerically compared the result to all of the resolved images of MU₆₉ that had been returned. The shape model was parametrically defined, separately for each lobe, using the "octantoid" formalism (30) (see methods). Our best-fitting shape model (Fig. 2) has overall dimensions of approximately 35 × 20 × 10 km, with estimated uncertainties of less than 1 × 1 × 3 km. The thickness (i.e., the third dimension) is the least

Fig. 1. Close approach 06 (CA06) MVIC observation of MU₆₉. (A) MVIC image made at a solar phase angle of 32.5°, a range of 6640 km, and a native pixel scale of 130 m per pixel, resampled to a 2× finer pixel scale and then deconvolved using a similarly resampled MVIC point-spread function. (B) Red-cyan stereographic anaglyph of the MU₆₉ approach hemisphere.

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well constrained because the spacecraft approach was at a high negative (i.e., southern) latitude on the object, so little of the positive (i.e., northern) half of MU69 was directly observed. From this shape model, the Ultima lobe was found to be lenticular with dimensions of approximately 22 × 20 × 7 km (uncertainty < 0.6 × 1 × 2 km), whereas the Thule lobe is more equidimensional, approximately 14 × 14 × 10 km (uncertainty < 0.4 × 0.7 × 3 km). The model volumes of Ultima and Thule are 1400 km³ (± <600 km³) and 1050 km³ (± <400 km³), respectively. The centers of the lobes are 16 km apart. The principal axes of the lobes are roughly parallel to one another (likely <7° misalignment), which strongly suggests that the lobes tidally locked prior to contact (see below).

The apparently lenticular shape of the Ultima lobe is unlike any other known heliocentrically orbiting Solar System body, but is reminiscent of some small ring satellites of Saturn, such as Atlas and Pan, which have accreted equatorial ridges of fine-grained material (31). The origin of this flattened shape of Ultima is indeterminate; possible explanations include accretion from a thin (i.e., flattened) particle sheet during pebble cloud collapse (24), the head-on collision of two very similarly sized bodies within a narrow range of speeds (32), or deformation arising from rapid rotation or tidal forces prior to its merger with Thule. These possibilities are discussed below.

Because no satellites of MU69 were detected (see below), MU69’s density is poorly constrained. Cometary nuclei are the Solar System bodies likely to be most similar to MU69; they are generally found to have low density (<10³ kg m⁻³) and high porosity (>50%) (27). The most precisely determined comet nucleus density is that of 67P/Churyumov-Gerasimenko, at 533 ± 6 kg m⁻³ (33), although it is unknown how much that comet’s density has evolved from its primordial value. Adopting the shape model in Fig. 2, a lower bound on MU69’s density of ~280 kg m⁻³ can be derived by assuming that MU69’s two lobes are only marginally bound by self-gravity and there is no tensile strength in the neck. Alternatively, assuming a characteristic cometary density of 500 kg m⁻³ (21) gives a breakup rotation rate for MU69 of ~12 hours. At this density, if the two lobes merged from a mutual circular orbit, substantial loss of angular momentum would have been required to reach their current, 15.92-hour period. Because mutual gravity would exceed centrifugal acceleration, densities greater than ~280 kg m⁻³ also imply that the neck region is currently under compression.

Fig. 2. Shape model for MU69. (A) The same MVIC image as Fig. 1A for comparison. (B) Shape model of MU69 based on approach rotational coverage and close flyby observations, seen at the same viewing and illumination conditions as (A). (C) to (E) Shape model seen along MU69’s z (C), x (D), and y (E) axes, with the object’s spin axis indicated in red. The arrow of the spin axis is the positive (i.e., north) pole. The shape of the +z hemisphere, which was mostly in darkness during the encounter, is the least well constrained part of the shape model.
We calculated the gravitational and rotational potential across the surface of \( \text{MU}_9 \) assuming the shape model in Fig. 2, a uniform density of 500 kg m\(^{-3} \), and its 15.92-hour rotation period. The surface acceleration ranges between 0.5 and 1 mm s\(^{-2} \) (and is nowhere negative). The local acceleration slopes (i.e., the gradients of the gravitational and rotational potential across the surface) are low except in the neck, where they can exceed 35\(^{\circ} \). The equators of Ultima and Thule are gravitational and rotational potential highs.

**Surface reflectivity, color, and composition**

Figure 3A shows a visible-wavelength I/F (reflected intensity divided by incident flux) contour map from the close approach 04 (CA04) LORRI observation (13\(^{\circ} \) solar phase angle) and its corresponding I/F histogram. At this solar phase angle, the modal I/F of \( \text{MU}_9 \) is 0.078. The I/F distributions of \( \text{MU}_9 \)'s two lobes have the same mode within the measurement error of ±0.05 I/F. I/F variations ranging from ~0.02 to ~0.12 are seen on both lobes (including their terminator regions). However, away from the terminator (i.e., the surface boundary between daylight and nighttime where lighting effects bias results), the minimum I/F is ~0.05. This occurs on a portion of the wall of the large depression on Thule, which we informally refer to as Maryland (surface features on Ultima Thule are informally named after U.S. states with major contributions to New Horizons); see Fig. 1. The maximum I/F of ~0.12 occurs at both of the bright spots in Maryland and on the neck region. The I/F distribution of the Ultima lobe has a sharper peak than that of Thule (Fig. 3B).

The brighter material on Ultima and Thule is mostly segregated into three kinds of surface manifestations: (i) nearly circular spots that become more numerous with decreasing size (ranging from a few kilometers across to the resolution limit of several tens of meters); (ii) curvilinear and quasi-linear features that are narrow relative to their length; and (iii) broad patches, which are more prominent on the Thule lobe. Darker than average surface units on the binary also come in types (i) and (iii), but not (ii).

It is unclear how these three types of comparatively bright terrain originated and how they may differ. However, initial stereographic analysis of New Horizons images using established techniques (94, 35) shows that many of the observed bright areas on \( \text{MU}_9 \) are located either within topographic depressions (e.g., the neck, the bright spots in Maryland, and the floors of pits and troughs) or at the bases or inflection points of slopes. Therefore, a possible explanation is that bright, fine-grained material has been transported downslope to these locations, in which case the higher brightness could be due to predominantly smaller particle size (36). However, other interpretations including compositional or thermal effects, space weathering, and cold trapping are also possible.

The neck feature at the Ultima-Thule merger zone might not have the same origin as other bright locales. Possibilities include (i) surface processes such as fine particle accumulation, as discussed above; (ii) processes related to the lobe merger, such as the extrusion of preexisting bright surface material on one lobe during the impact; (iii) post-impact thermal extrusion of ices due to changes in thermal properties or conditions at the merger zone after contact; and (iv) evolutionary processes such as preferential space-weathering effects or thermal effects created by the geometry surrounding the neck.

Analyses of the approach and departure images have allowed us to characterize the solar phase curve of \( \text{MU}_9 \) at phase angles up to 153\(^{\circ} \); considerably higher than possible for Earth-based observations of this object, which are limited to ~2\(^{\circ} \) (Fig. 4). The derived phase coefficient, or slope, is \( \beta = 0.038 \pm 0.014 \) magnitudes per degree, between 1.3\(^{\circ} \) and 32.5\(^{\circ} \). This slope is consistent with that measured for other low-albedo small Solar System bodies, including comet nuclei [e.g., (37)]. Applying a Hapke photometric model (36) to the entire phase curve yields the nominal photometric properties of \( \text{MU}_9 \)'s surface: single scattering albedo \( \alpha_0 = 0.24 \), mean topographic slope angle \( \theta = 39^{\circ} \), and single-particle phase function parameters using a McGuire-Hapke formalism (37) of \( b = 0.32 \) and \( c = 0.75 \). These results give \( \text{MU}_9 \)'s visible (0.55-\mu m V-band) geometric albedo (i.e., the albedo at 0° solar phase) of \( m_p = 0.165 \pm 0.01 \). This is a typical value for CCKBOs, the geometric albedos of which range from 0.09 to 0.23, with a mean of 0.15 (38). \( \text{MU}_9 \)'s phase integral is \( q = 0.37 \pm 0.16 \), yielding a spherical (Bond) albedo of 0.061 ± 0.026. MVIC color images reveal a globally averaged visible-wavelength reddish reflectance slope of 31.1 ± 0.5% per 100 nm, computed using MVIC’s blue, red, and near-IR filters (Fig. 5, A to C), where the quoted uncertainty here is statistical only. This color is consistent with that of other CCKBOs (39-41). Only subtle color (and spectral; see below) differences (and spectral differences; see below) are detected between the two lobes of \( \text{MU}_9 \), despite their distinct shapes and appearances. The two lobes are clearly resolved from one another at the resolution of the color data. Remote observations of KBOs with satellites show near-equal colors of the orbiting bodies, interpreted as resulting from co-accretion from a locally homogeneous portion of the nebula (42).

The clearest regional color and spectral signatures across \( \text{MU}_9 \)'s surface appear (i) at the neck between the two lobes, and (ii) at the Thule lobe bright spots in Maryland, which display spectral slopes of 28.2 ± 0.2% per 100 nm and 30.8 ± 0.2% per 100 nm, respectively. At least two locations on the Ultima lobe also show less red than its average color. Principal components analysis shows that 97% of the variance in MVIC color data is attributable to shading and albedo, whereas image noise and true color contrasts account for just 3%. The subtle color differences seen could be indicative of compositional differences, although differences in particle size, porosity, etc., can also produce differences in spectral slopes.

LEISA spectral observations (Fig. 5D; see methods) show that \( \text{MU}_9 \) is brighter in the near-IR than it is in the visible spectrum, demonstrating that the red slope observed using MVIC extends into the IR. From 1.2 to 2.5 \( \mu \)m, the observed I/F after radiometric calibration ranges from 0.15 to 0.2. The colorant responsible for the redness of \( \text{MU}_9 \) and other CCKBOs could be tholin-like complex organic macromolecules, produced from simpler species through radiolytic and photolytic breaking of bonds leading to recombination into progressively heavier molecules [e.g., (43, 44)]. Space weathering of silicates can also produce a red coloration, but no direct evidence of silicates is seen on \( \text{MU}_9 \). Principal components analysis shows that more than 90% of the variance in the LEISA data is also due to shading and albedo, with relatively little variance attributable to regional spectral variability.

As shown in Fig. 5D, there are key color slope similarities between the spectrum of \( \text{MU}_9 \) and...
Temperatures on MU69 are set by the balance between the absorption of sunlight and thermal emission back to space. For the 6% Bond albedo estimated above, and an assumed 90% emissivity, absorption and emission at MU69's mean distance from the Sun are balanced at 42 K. For plausible values of thermal conductivity in the $10^{-5}$ J m$^{-1}$ s$^{-1}$ K$^{-1}$ range, we estimate the characteristic skin depths to which diurnal and seasonal waves propagate to be ~0.001 m and ~1 m, respectively (see methods). Therefore, diurnal and seasonal temperature variations likely only affect the outer few millimeters to meters of MU69’s surface, so the average temperature pertains to the vast majority of MU69's interior. At this 42 K temperature, frozen volatile species such as CO, N$_2$, and CH$_4$ not trapped in clathrates would sublime and escape relatively rapidly compared to the age of the Solar System, but amorphous H$_2$O ice would not crystallize and so could survive over the age of the Solar System.

Near the surface of MU69, temperature varies on seasonal and diurnal time scales. As a result of MU69’s low orbital eccentricity, insolation only differs by 17% over the course of its orbit. However, summer/winter hemisphere insolation varies considerably over MU69’s 293-year orbit because of the 98° obliquity of its pole, resulting in long polar days and nights during which regions receive continuous sunlight, or none at all, for many decades. Around equinox, the 15.92-hour rotation period would also produce strong diurnal variations in insolation. Changing insolation generates thermal waves as heat is conducted into and out of the subsurface.

We expect summer surface temperatures to approach a maximum instantaneous equilibrium temperature of ~60 K, whereas winter temperatures (as on the unilluminated face of MU69 during the New Horizons flyby) are much lower, down to the seasonal skin depth. Analysis of the REX radiometry data at the 4.2-cm X-band radio wavelength indicates a brightness temperature in the 20 to 35 K range on the winter (night) side of MU69. Thermal emission at centimeter wavelengths emerges from a range of depths, potentially up to many tens of wavelengths below the surface, so the warmer subsurface is an important source of flux. For typical icy satellite emissivity at centimeter wavelengths (52, 53), the observed REX brightness temperature range appears to be consistent with the expected low thermal inertia values estimated for other KBOs (52).

**Geophysical and geological properties**

We measured the limb profile of MU69 using previously published techniques (53). These limb profiles (Fig. 6A, 6B, and 6C) were derived from the CA04 LORRI (characteristic 140 m per pixel) and CA06 MVIC (characteristic 130 m per pixel) observations and were compared with best-fitting ellipses for the projected shape of each lobe. The elliptical axes remove the long-wavelength signal and are not necessarily representative of the 3D body shape (i.e., they are not measured with respect to the shape model in Fig. 2).

On the larger lobe Ultima, the limb topography shows total (i.e., minimum to maximum deviation) relief of ~1 km, whereas the relief on the smaller lobe Thule is more muted at ~0.5 km. Assuming a density $\rho = 500$ kg m$^{-3}$, a surface gravity $g = 0.001$ m s$^{-2}$, and topography of vertical scale $h = 0.5$ to 1 km implies stresses on the order of $gh/h$, or ~100 Pa. Such modest stresses can be supported by friction. Excessively steep regions (>35°) near MU69’s neck likely require additional internal strength to remain stable. Cohesion of several hundreds of pascals would be capable of supporting these slopes. Such strengths are thought to be normal for comet-like bodies (22) and so are plausible for KBOs of MU69’s size as well.

A geomorphological map of MU69 is shown in Fig. 6C. The two lobes have somewhat different surface geology. Thule’s surface is dominated by Maryland, a depression of probable impact origin (unit labeled ‘i’; see Fig. 6C for key to these abbreviations), ~7 km in diameter (see above). Stereographic analysis shows that the depth of Maryland is ~0.5 km; this depth is consistent with the observed limb topography variations. Maryland’s interior shows no unambiguous signs of horizontal layering but does contain two prominent bright spots of similar size and albedo. Two distinct, kilometer-scale, possible impact craters occur on Maryland’s rim crest. Separately, four distinct troughs appear near the terminator of Thule in unit ‘um’.

Apart from Maryland, the rest of Thule’s observed surface is characterized by broad (few kilometers wide), dark swaths (unit ‘dm’) that separate lighter-toned, mottled units (units ‘pm, um, and ‘rn’). In some places, these dark swaths contain bright spots and a bright-floored, quasi-linear...
trench. The crenulated boundaries of unit *dm* may be a decrescence morphology, whereby this unit is partly bounded by scarps that have retreated. Unit *dm* may be a deposit of volatile ice with bounding scarps forming as a result of sublimation at its periphery, with the upper surface of the deposit being protected from sublimation by a dark, refractory mantle, perhaps derived from the deposit itself (54, 65). Portions of unit *um* that are proximal to Maryland may be ejecta from the crater, or related to ejecta, but this cannot be confirmed with the current analysis. A distinct, relatively bright region (unit *rm*) at the equatorial, distal end of Thule exhibits roughness at the scale of a few hundred meters; some of the features there appear to be pits, craters, or mounds.

A lightly cratered surface of MU₆₉ was predicted by a recent cratering model (23); indeed, few definitively impact-related scars are identified on MU₆₉. We have considered several hypotheses for the origin of the many pits seen near the terminator in Fig. 2A. These include structurally controlled collapse pits, outgassing pits, sublimation pits, and impact craters (56); they likely are not all created by the same process. Our assessment is that the chains of similarly sized pits are more likely to be formed by internal processes than by cratering, but the isolated pits that show approximately circular planform outlines, bowl-shaped interior depressions, and, in some cases, raised rims are more consistent with impact crater morphology. There are no obvious crater candidates that are intermediate in size between these ~1-km-diameter pits (unit *sp*) and Maryland (unit *lc*, ~7 km).

On Ultima, eight similarly sized (~5 km scale) units of rolling topography (based on subtle albedo gradations and limb profiles) dominate its observed landscape (units *ma* to *mh*). The albedo and texture of these units are generally similar to one another, although each contains brighter material to differing degrees. These units abut each other, typically bordered with distinct, curvilinear, and generally higher-reflectance boundary regions (particularly unit *mh*, which is ringed by a brighter annulus). In one instance (near the terminator), a trough and a short pit chain mark such a boundary, but the low solar incidence angles prevailing across much of Ultima make it unclear whether the boundaries are always associated with topographic features. Stereographic analysis indicates that most of these units have broadly positive relief, although the central unit *mh* is relatively flatter. It is also unclear whether these boundaries necessarily imply superposition relationships among the components. One unit, at the limb of Ultima (unit *md*), appears to be more angular in stereography and is either more elevated or tilted with respect to the other components.

The apparent similarity in the size of Ultima’s units (ma through *mh*) is likely a clue to their origin. Whether they are a relic of Ultima’s formation or a result of a later evolution is unclear. One formation-related hypothesis is that the individual units on Ultima are accretional subunits of smaller planetesimals that formed Ultima. This apparent assemblage of units on Ultima is consistent with observation of and proposals for the formation of layers on comets such as 9P/Tempel and 67P/Churyumov-Gerasimenko (20, 67). However, challenges to this hypothesis are the apparently (i.e., at the available resolution) nearly unimodal size of these units and their apparent absence from Thule, although the latter could be the result of resurfacing caused by the Maryland cratering event. Also, at the
expected impact speeds during accretion, such as in a local particle cloud collapse resulting in a body like \( \text{MU}_{69} \) (perhaps no more than a few meters per second, based on the mutual escape speed of the lobes), these accretional subunits would likely not be expected to merge into as compact a body as Ultima unless they were extremely weak (i.e., cohesionless and frictionless) at the time of their accretion (22).

**Satellites and orbiting rings/dust search**

Both satellites and rings have been detected around KBOs larger than \( \text{MU}_{69} \) and around Centaurs (16, 58, 59), which have escaped the Kuiper Belt and now orbit among the giant planets. Although no KBO as small as \( \text{MU}_{69} \) is known to have rings, satellites around KBOs are common, particularly in the CCKBO population (16).

We searched for satellites and rings of \( \text{MU}_{69} \) using co-added stacks of LORRI images acquired during approach to \( \text{MU}_{69} \) at exposure times of 10 to 30 s. High-resolution images taken near closest approach provide additional constraints on satellites close to \( \text{MU}_{69} \). No satellites were detected in our data. Figure 5A shows the quantitative limits on satellites obtained from these data as a function of distance from \( \text{MU}_{69} \).

Additionally, small particles orbiting \( \text{MU}_{69} \) could form ring or other dust structures with unusual geometries (80) because \( \text{MU}_{69} \)'s very weak gravity is of similar magnitude to the solar radiation pressure. However, larger grains, which are less affected by solar radiation pressure, could form a conventional equatorial ring (80).

Approach images constrain any ring or dust assemblages located ≥250 km from \( \text{MU}_{69} \) to have \( I/F \leq 2 \times 10^{-7} \) (for a 10-km-wide ring) at a phase angle of 11° (Fig. 7B). This is equal to or less than the \( I/F \) of many faint outer rings of the giant planets, which have ring widths of >20 km (61, 62). A single downlinked high-phase (165°), forward-scattered observation also shows no evidence for rings or dust farther than ~400 km from \( \text{MU}_{69} \) at \( I/F > 10^{-4} \). The VBSDC dust counter experiment reported zero dust impact detections during the passage through the gravitational stability sphere of \( \text{MU}_{69} \), consistent with a lack of extant rings or other dust assemblages.

**Exosphere and heliospheric interaction searches**

Because of \( \text{MU}_{69} \)'s small size, it is likely that highly volatile ices that might once have been present at its surface would have escaped to space long ago (6, 56). However, less volatile ices (e.g., methanol, acetylene, ethane, and hydrogen cyanide) could be retained over geological time scales, and irradiation of these species could result in reddening over time as longer-chain tholins are produced (e.g., methanol, acetylene, ethane, and hydrogen cyanide) could be retained over geological time scales, and irradiation of these species could result in reddening over time as longer-chain tholins are produced (63, 64). This implies a slow loss of hydrogen atoms to space as surface ices are converted into tholins. In addition to this escaping H flux, occasional large impacts could provide a source for a transient atmosphere.

We searched for evidence of both a coma of escaping gas and charged particle emissions from \( \text{MU}_{69} \). The searches included use of the Alice ultraviolet spectograph to search for resonance line emission from a coma, as well as in situ searches for emitted \( \text{MU}_{69} \) ions with SWAP and PEPSI.

An Alice count rate spectrum is shown in Fig. 6A. This observation was made over a period of 300 s, ~90 min before closest approach, from a range \( r \approx 80,000 \) km. We fitted a model to the spectrum including background emissions from interplanetary hydrogen plus four nearby stars. No coma emissions from \( \text{MU}_{69} \) were detected. At the brightest likely coma emission of the hydrogen 121.6-nm line, we find a 3σ upper limit.
source rate of $<3 \times 10^{24}$ H atoms s$^{-1}$ released by MU$_{69}$. Scattering of sunlight by H atoms at this source rate would produce a detectable emission, assuming a distribution that falls off as $r^{-2}$ from MU$_{69}$.

No structured magnetic interaction between the solar wind and MU$_{69}$ was expected because, at a typical interplanetary magnetic field of 0.2 nT, the gyro-radius of a proton picked up by the solar wind is ~2 x 10$^4$ km; this distance is larger than the gyro-radius of a proton picked up by the solar wind. A fraction of H atoms to get from MU$_{69}$ to the Sun is <3 x 10$^{-17}$ Hz at MU$_{69}$ of 1.6 x 10$^{12}$ photons m$^{-2}$ s$^{-1}$ and 4.0 x 10$^{11}$ photons m$^{-2}$ s$^{-1}$, respectively (68, 66), and a yield of 0.003 for H 121.6-nm scattering of sunlight by H atoms at this point in space is ~2.4 x 10$^7$ H atoms km$^{-1}$, much less than our detection limit from Alice. For an outflow source rate of <3 x 10$^{24}$ H atoms s$^{-1}$ released by MU$_{69}$, the Hill radius (i.e., maximum orbit stability radius against tidal forces) shown here assumes an effective spherical-equivalent radius of 7.5 km for MU$_{69}$ (approximating the lobes as ellipsoids) and a density of 500 kg m$^{-3}$. The binary size ratios produced in existing pebble cloud collapse models (24), while focused on the formation of much more massive (100-km scale), co-orbiting binaries, are also consistent with the size ratio of the two lobes of MU$_{69}$ (size ratio $\approx$ 0.75). Such models also produce appropriately low merger speeds (24, 25) if they scale with the virial mass to much smaller clouds. However, MU$_{69}$’s pole is highly inclined to the ecliptic, which is not a common outcome in cloud collapse models, given that the cloud’s initial rotation state is set by heliocentric Keplerian shear. In contrast, turbulent particle concentration models, such as an overdense collection of swirling particles collapsing under the influence of aerodynamic drag in the protosolar nebula (73), have no preferred initial swirl (mean angular momentum) orientation.

Mechanisms fundamentally different from local pebble or particle cloud collapse have also been proposed for the formation of small-body binaries. However, some such mechanisms, such as YORP spin-up and fission (28, 29), apply only in the inner Solar System where thermal radiation forces are sufficiently strong. In the outer Solar System, binary systems may instead form via three-body exchange capture (74), but such mechanisms require heliocentric encounter velocities generally near or lower than the Hill speed [the heliocentric Keplerian shear speed at the limit of the primary body’s gravitational sphere of influence (24)], which for MU$_{69}$ would have been an implausibly low ~1 cm s$^{-1}$; hence, such models are disfavored. We also do not favor this three-body formation mechanism because binaries formed by such three-body exchange would likely rotate either prograde or retrograde (24, 75), not highly obliquely like MU$_{69}$.

For MU$_{69}$’s two lobes to reach their current, merged spin state, they must have lost angular momentum if they initially formed as co-orbiting bodies. The lack of detected satellites of MU$_{69}$ may imply ancient angular momentum sink(s) via (i) the ejection of formerly co-orbiting smaller bodies by Ultima and Thule, (ii) gas drag, or
Fig. 8. MU69 atmospheric and plasma search results. (A) Alice ultraviolet airglow spectrum. A modeled background (blue) includes interplanetary H emissions and four nearby stars. A small model signal at 116.6 nm (gold) indicates the H 121.6 nm count rate that would be expected if MU69 were outgassing H atoms at $Q \approx 3 \times 10^{24}$ atoms s$^{-1}$; the 121.6-nm H signal appears at this wavelength because the observations were offset to avoid a low-sensitivity region of the detector. No MU69 coma emission is detected in the observed spectrum (black). (B and C) SWAP low-energy plasma spectrometer data showing light (blue) and heavy (orange) secondary channel electron multiplier (SCEM) count rate energy/charge spectra, where light (i.e., H$^+$ and He$^{++}$) and heavy ions are distinguished by their low and high secondary/primary electron ratios as they pass through SWAP’s carbon foil (65), and coincidence rates (COIN) spectra. The heavy ions are sparse and are not associated with close approach. (D and E) SWAP orientation with respect to the Sun in altitude ($\theta$) and azimuth ($\phi$) angles (black, full range; red, zoomed). All the changes observed in the coincidence rate spectra in (B) and (C) are associated with changes in spacecraft orientation; no changes related to the presence of MU69 were observed. (F to I) PEPSSI energetic particle spectrometer data. Count rates are shown for three products for ~80 min near closest approach to MU69 (indicated by the vertical black line). Data were acquired in 1-s bins but averaged over 2-min intervals to improve the signal-to-noise ratio. (F) Suprathermal particles at $>$2 keV nucleon$^{-1}$ (dominated by interstellar pickup He$^+$); (G) energetic protons (30 keV to 1 MeV); (H) galactic cosmic rays (mostly $>$100 MeV protons); (I) the angle between PEPSSI aperture and the Sun. Changes in instrument orientation account for all the observed count rate variability; all particle rates shown are typical for the undisturbed interplanetary medium, with an increased photon background when the Sun is in the PEPSSI field of view (FOV).
both. This suggests that contact binaries may be rare in CCKBO systems with orbiting satellites. Another possibility, however, is that the lobes Ultima and Thule impacted one another multiple times, shedding mass along with angular momentum before making final contact. But the alignment of the principal axes of MU69’s two lobes tends to disfavor this hypothesis. In contrast, tidal locking could quite plausibly have produced the principal axis alignment we observe, once the co-rotating bodies were close enough and spin-orbit coupling was most effective (76).

Gas drag could also have played a role in fostering the observed coplanar alignment of the Ultima and Thule lobes (Fig. 2). Post-merger impacts may have also somewhat affected the observed, final angular momentum state.

Methods
Shape model fitting process

Because the pole and rotation rate of MU69 were not known before the New Horizons flyby, it was necessary to simultaneously fit the shape and pole of the object. The data available to accomplish this were the resolved images of MU69 that were obtained from a few days prior to closest approach up to closest approach itself. The problem was broken into parameters for pole, rotation rate, mean surface albedo, and a parametrically defined shape. Each of the two lobes of the KBO was defined with its own parametric model; the separation between the lobes was made an additional free parameter. The “octantoid” formalism was used for the lobes (30), which is similar to spherical harmonics but is precisely an ellipsoid at the lowest order. Starting by assuming that both lobes are ellipsoids, increasing complexity and spatial resolution were then added to the shape model by increasing the harmonic orders of the octantoids. Images were converted to radiometrically calibrated I/F space to minimize the work the fitting program would have to do.

To test this parameter set against the data, synthetic versions of the resolved images were generated as follows. First, the parametric shape was rastered onto a 3D mesh for each lobe, and the surface normals for each polygon in the mesh were calculated. Next, the geometry for the image was calculated, using the navigation SPICE kernels (77) for distance to MU69 and the World Coordinate System (WCS) for pixel scale and image rotation. The mesh was then rendered in OpenGL using the derived geometry. The renders were performed twice, once to provide a depth buffer and a second time that used the depth buffer to allow soft-shadowing on the object. The second rendering also calculated the brightness for each pixel of the image in I/F space, using the Hapke photometric model described in the text. Performing the rendering in OpenGL allowed the work to use GPUs to speed up the shape-fitting process. The rendered images from each New Horizons camera were then convolved with the point-spread function of that camera. This smeared out the rendered images to the same angular resolution as the real images, allowing direct comparison of the images on a pixel-by-pixel basis, even in the early images in which MU69 was only a few pixels long. Finally, the sum of the square of the difference of each real image was compared to its simulated version; a sum of all of those differences provides an estimate of the \( \chi^2 \) for any derived parameter set.

With the problem now reduced to a parameter set and a \( \chi^2 \) function, standard function-minimization techniques were used to find the optimal shape and pole. As noted above, this started with simple ellipsoidal shapes for each lobe, which were used to find initial solutions for the pole, rotation, and obliquity. Next, the complexity of the model shapes was gradually increased as new images were incorporated. The number of images fitted and the complexity of the model both increased the time to calculate \( \chi^2 \) for any parameter set, and thus increased the time required for the optimization process. This in turn limited the spatial resolution of the shape model.

LEISA data processing

The IR spectral imaging spectroscopy capability on New Horizons is provided by the LEISA instrument (78). LEISA’s focal plane consists of a 256 × 256 HgCdTe detector array with a linear variable filter affixed to it such that each row of the array is sensitive to a different IR wavelength between 1.2 and 2.5 \( \mu m \). Its average spectral resolving power \((\lambda/\Delta \lambda)\) is close to 240. LEISA is operated by sweeping its field of view across the target scene while images are recorded at a frame rate of approximately 1 frame per pixel moved, so that each part of the scene is recorded in each of LEISA’s wavelengths. The highest spatial resolution LEISA scan of MU69 was designated CA04_LE. This scan can also be identified by its unique Mission Elapsed Time (MET) number, 0408624118; it was obtained about 4:58 UT on August 18, 2021.

Attitude data reported by the spacecraft were used to account for the motion of the target through the LEISA field of view. This motion was complex because spacecraft pointing was controlled by frequent thruster firings to maintain pointing within a specified amount. Over the course of the scan, the spacecraft closed range with the target, from approximately 33,000 to 29,000 km. This changing geometry resulted in a wavelength-dependent scale in the spectral image cube. To correct for this effect in extracting the spectrum shown in Fig. 5D, the region of interest for spectral extraction was constructed using the same wavelength-dependent scale. The diminished solar flux at 43 AU, combined with the low albedo of MU69, produces a signal level similar to the noise in a single LEISA pixel; so multiple pixels had to be averaged together to produce the spectrum in Fig. 5D. The scatter of the points gives an indication of the noise in the resulting average spectrum. Spectral models of granular combinations of H\(_2\)O and CH\(_3\)OH ices with tholins are able to reproduce the overall albedo and features in the LEISA spectrum, except for the unidentified band at 1.8 \( \mu m \).

Thermal models

Incident sunlight varies across MU69’s surface over its 293-year orbit around the Sun and also its 15.92-hour rotation about its spin axis, causing time-variable temperatures. The local radiative balance is also affected by topography, especially in the neck region, where greater shadowing reduces incident sunlight but also reduces the solid angle of dark sky into which thermal emission can be radiated. Heat propagating inward or outward moderates insolation-driven surface temperature variations, with thermal inertia \( \Gamma \) (the square root of the product of heat capacity \( c \), density \( \rho \), and conductivity of the material \( k \)), with units of \( J m^{-2} s^{-1/2} K^{-1} \) controlling the degree of moderation. The thermal waves penetrate to a characteristic skin depth, \( d_{\text{skin}} = (2k/\rho c)^{1/2} \), where \( \omega \) is the angular frequency of the temperature forcing. Conductivity is the least certain of these parameters, being sensitively dependent on the material texture and temperature. It is generally low for cold, granular materials in vacuum, and the expectation for MU69 is for very loosely consolidated material. This follows from the low expected bulk density of MU69, as well as from thermal observations of other KBOs. Herschel and Spitzer space telescope observations have shown a mean diurnal thermal inertia for Centaurs and KBOs of \( \sim 2.5 \ J m^{-2} s^{-1/2} K^{-1} \) (52).

Assuming a bulk density of 500 kg m\(^{-3}\) and a heat capacity of 350 J kg\(^{-1}\) K\(^{-1}\) of H\(_2\)O-ice at 40 K (79), a \( \Gamma \) of 2.5 J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\) implies a very low conductivity of approximately 3.6 × 10\(^{-7}\) J m\(^{-1}\) s\(^{-1}\) K\(^{-1}\). If instead we follow (80, 81) and assume that ice \( \text{I}_{\text{H}} \) is the dominant constituent, such a low conductivity would require a porosity of \( \sim 65\% \), not unreasonable for a bulk density of 500 kg m\(^{-3}\).

Low thermal inertia and low conductivity imply that surface temperatures on MU69 are close to instantaneous equilibrium between absorbed insolation and thermal emission. The low conductivity implies that the thermal waves driven by diurnal and seasonal insolation variations affect only the very outermost layers, with \( d_{\text{skin}} \sim 0.001 \) m and \( \sim 1 \) m, respectively. The seasonal skin depth could be somewhat greater if conductivity increases with depth below the surface. MU69 could have an even lower thermal inertia than the much larger objects in the Herschel and Spitzer sample, given that its lower mass and sparseness of impact craters imply less collisional compaction over time and that its smaller size limits the possibility of early heating by short-lived radionuclides that might have led to sintering and thus higher thermal conductivity in larger objects.
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Initial results from the New Horizons exploration of 2014 MU₆₉, a small Kuiper Belt object

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New Horizons flies past MU₆₉

After flying past Pluto in 2015, the New Horizons spacecraft shifted course to encounter (486958) 2014 MU₆₉, a much smaller body about 30 kilometers in diameter. MU₆₉ is part of the Kuiper Belt, a collection of small icy bodies orbiting in the outer Solar System. Stern et al. present the initial results from the New Horizons flyby of MU₆₉ on 1 January 2019. MU₆₉ consists of two lobes that appear to have merged at low speed, producing a contact binary. This type of Kuiper Belt object is mostly undisturbed since the formation of the Solar System and so will preserve clues about that process.

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