OUTER SOLAR SYSTEM

Color, composition, and thermal environment of Kuiper Belt object (486958) Arrokoth

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INTRODUCTION: The New Horizons spacecraft flew past (486958) Arrokoth (provisional designation 2014 MU₆₉) on 1 January 2019. Arrokoth is a member of the subclass of trans-neptunian or Kuiper Belt objects (KBOs), known as the cold classical KBOs (CCKBOs). Most KBOs formed in a disk of planetesimals that extended to about 30 AU from the Sun. Neptune eventually disrupted that disk by migrating outward through it, with the migration halted by the sparseness of the disk beyond 30 AU. That event eliminated most members of the planetesimal disk, but a minority were emplaced into dynamically excited orbits in the present-day Kuiper belt. CCKBOs differ from those objects in having formed well beyond the 30-AU edge of the main planetesimal disk. They remain approximately where they formed, on low-inclination, near-circular orbits between 42 and 47 AU from the Sun, relicts of the early Solar System. Their distributions of colors, albedos, sizes, and binarity differ from those of the more excited KBOs.

RATIONALE: Initial results from the exploration of Arrokoth were published previously. More data have since been received from the spacecraft, allowing a more detailed analysis. We analyze a high-spatial resolution color imaging observation, near-infrared spectral imaging, and microwave radiometry of Arrokoth. The infrared spectral data have been processed to compensate for the changing range and scale during the observation. Our multiple scattering radiative transfer models provide compositional constraints from the infrared spectral imagery. Microwave thermal radiometry at 4.2-cm wavelength is combined with heat transport models that account for the bilobate shape of Arrokoth and for self-radiation.

RESULTS: At visual wavelengths, Arrokoth’s reflectance rises toward longer wavelengths. This red coloration is typical of the broader CCKBO population that has been studied using telescopic observations. Color differences across the surface of Arrokoth correspond to geological features. These color differences are subtle, with deviations of just a few percent around the prevailing red coloration. Some of the color variations are associated with albedo markings, such as the bright neck between the two lobes, bright splotches associated with a large pit or crater on the smaller lobe, and poorly resolved small bright spots. Methanol ice (CH₃OH) and complex organic tholins dominate the near-infrared reflectance spectrum, with H₂O ice contributing little or no detectable absorption. At the 4.2-cm microwave wavelength of New Horizons’ radio system, Arrokoth’s winter night side glows with an average brightness temperature of 29 ± 5 K. This emission probably emerges from below the cold winter surface, at depths where warmth from the previous summer lingers. Our models show that self-radiation more than compensates for self-shadowing in the neck region between the two lobes, resulting in warmer temperatures in that region, by up to a few kelvin.

CONCLUSION: The nearly uniform coloration across Arrokoth is consistent with expectations for an object that accreted too quickly for the composition of the available nebular solids to have changed during the course of its accretion. Radiolysis and photolysis from long exposure to space radiation would be expected to result in a dark, space-weathered surface veneer that is distinct from the more pristine interior, but there is little evidence for such a coating, perhaps because radiolytically processed material is eroded away faster than it accumulates. The abundance of CH₃OH ice and apparent scarcity of H₂O ice appear to be signatures of a distinct environment in the cold, dust-shaded midplane of the outer nebula during formation of the Solar System. In this region, temperatures would have been low enough that volatile CO and CH₄ could freeze onto dust grains, enabling production of CH₃OH and perhaps also destruction of H₂O. When the nebular dust dissipated some time after Arrokoth’s formation, exposure to sunlight would have raised its temperature, rapidly driving off condensed CO and CH₄. The temperature has remained too cold to crystallize amorphous H₂O. Volatile species may remain trapped in amorphous H₂O ice within Arrokoth’s interior, but the infrared spectrum shows little evidence for such ice at the surface. Although the neck region gets slightly warmer than the rest of Arrokoth’s surface, this effect is small relative to the winter-summer temperature contrast and is thus unlikely to account for the distinctly higher albedo and slightly less red material that is seen there. A more plausible explanation for the neck’s albedo and color contrasts involves texture changes induced by the merger of the two lobes or subsequent downslope movement of material there.

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The new Solar System object (486958) Arrokoth (provisional designation 2014 MU₆₉) has been largely undisturbed since its formation. It was studied its surface composition using data collected by the New Horizons spacecraft. Methanol ice is present along with organic material, which may have formed through irradiation of simple molecules. Water ice was not detected. This composition indicates hydrogenation of carbon monoxide–rich ice and/or energetic processing of methane condensed on water ice grains in the cold, outer edge of the early Solar System. There are only small regional variations in color and spectra across the surface, which suggests that Arrokoth formed from a homogeneous or well-mixed reservoir of solids. Microwave thermal emission from the winter night side is consistent with a mean brightness temperature of 29 ± 5 kelvin.

Specifically, a member of the “kernel” subpopulation of the cold classical Kuiper Belt Objects (CCKBOs) (4). The origins and properties of CCKBOs are distinct from those of KBOs on more excited orbits, which are thought to have formed closer to the Sun before being perturbed outward by migrating giant planets early in Solar System history (5). CCKBOs still orbit where they formed in the protoplanetary nebula (the accretion disk of gas and dust around the young Sun). CCKBOs have a high fraction of binary objects (6), a uniformly red color distribution (7, 8), a size-frequency distribution deficient in large objects (9, 10), and higher albedos (11, 12) than other KBOs. These properties arise from the environment at the outermost edge of the protoplanetary nebula, from a distinct history of subsequent evolution of CCKBOs relative to other KBOs, or from some combination of these two. Arrokoth provides a record of the process of forming planetesimals—the first generation of gravitationally bound bodies—that has been minimally altered by subsequent processes such as heating and impactor bombardment (3).

Its distinctive bilobed, 35-km-long shape with fewer impact craters favors formation via rapid gravitational collapse, rather than scenarios involving more gradual accretion via piecewise agglomeration of dust particles to assemble incrementally larger aggregates (13). We study Arrokoth's color, composition, and thermal environment using data from the New Horizons flyby and discuss the resulting implications for its formation and subsequent evolution.

**Instruments and data**

New Horizons encountered Arrokoth when it was 43.28 AU from the Sun, collecting data with a suite of scientific instruments. Color and compositional remote sensing data were provided by the Ralph color camera and imaging spectrometer, sensitive to wavelengths between 0.4 and 2.5 μm (14). Over this wavelength range, all light observed from Arrokoth is reflected sunlight, with the wavelength dependence of the reflectance indicative of surface composition and texture. Ralph's two focal planes share a single 75-mm aperture telescope using a dichroic beamsplitter. The Multispectral Visible Imaging Camera (MVIC) provides panchromatic and color imaging in four color filters: BLUE (400 to 550 nm), RED (540 to 700 nm), NIR (780 to 975 nm), and CH4 (860 to 910 nm) (15). The highest-spatial resolution MVIC color observation of Arrokoth, designated as CA05, was obtained on 1 January 2019 at 05:14 UTC (coordinated universal time), from a range of 17,200 km, at an image scale of 340 m per pixel and phase angle of 15.5°. This provides more spatial detail than the CA02 MVIC color scan at 860 m per pixel (1).

Ralph's Linear Etalon Infrared Spectral Array (LEISA) images its target scene through a linear variable filter covering wavelengths from 1.2 to 2.5 μm at a spectral resolving power of about 240. Frames are recorded while the spacecraft scans LEISA's field of view across the scene; this enables each location to be captured at each wavelength of the filter. The highest-spatial resolution LEISA observation, designated as CA04, was executed around 04:58 UTC; shortly before the CA05 MVIC observation, from a phase angle of 12.6° and a mean range of 31,000 km, resulting in a mean image scale of 1.9 km per pixel (15).

New Horizons' panchromatic Long-Range Reconnaissance Imager (LORRI (16)) is co-aligned with Ralph and can record images while the spacecraft is scanning for a Ralph observation. Such LORRI observations, referred to as “riders,” are limited to short integration times to minimize image smear from scan motion, but multiple images can be recorded and combined in postprocessing, providing for longer effective integration times (3). LORRI rider observations were obtained during both the CA04 and CA05 observations, providing higher-spatial resolution context images for the Ralph observations.

New Horizons' Radio Science Experiment (REX (17)) was used to observe thermal emission in the X-band (4.2-cm wavelength, 7.2 GHz) from Arrokoth's Sun-oriented face on approach and then from its anti–Sun-oriented face on departure. The two REX observations, designated as CA03 and CA08, respectively, were obtained on 1 January at mean times of 04:34 and 05:52 UTC, phase angles of 11.9° and 162.0°, and ranges of 52,000 and 16,700 km, at those
distances, Arrokoth was unresolved, appearing much smaller than the 1.2° width (at 3 dB) of the high-gain antenna beam. Two independent receivers recorded the radio flux density in different polarizations at a sampling rate of 10 Hz. The REX A receiver recorded right circularly polarized flux while REX B recorded left circularly polarized flux.

**Visible-wavelength**

The CA02 MVIC color scan (1) had shown Arrokoth to be red but revealed little spatial variation in color. The higher-resolution CA05 observation allows us to better quantify Arrokoth’s regional color variations. Figure 1 compares the CA05 color image with the contemporaneous LORRI panchromatic rider image. Color slopes, computed by fitting a linear model to the MVIC BLUE, RED, and NIR filter reflectance data, are shown in Fig. 1C. All of Arrokoth’s surface is red in color, with a mean color slope of 27% rise per 100 nm relative (at 550 nm). This quantification of color slopes is commonly used for KBOs, being convenient for comparison of colors obtained using different filter sets (18). Even in the higher spatial resolution of the CA05 observation, the color distribution is largely uniform across the observed face of Arrokoth, with a standard deviation in slope of only ±2.7% per 100 nm.

Subtle regional color differences correspond to specific geological and albedo features discussed in a companion paper (3). The smaller lobe (SL) appears slightly redder on average than the larger lobe (LL) [28 ± 2% average slope versus 27 ± 2% for LL, where the ±2 values represent the variance across each lobe, rather than the uncertainty in the measurement of the mean slopes, which is much smaller for averages over many pixels (15)]. That difference appears to be mostly due to the redder rim (color slope 30 ± 2%) of a 6-km-diameter depression on SL, a possible impact crater informally designated as Maryland (MD; all place names are informal). Statistically significant color differences tend to be on similarly small (or smaller) spatial scales. Several slightly less red regions appear as blue in the color scale used in Fig. 1C. These include the brighter neck region where the two lobes intersect (25 ± 1% slope) and several regions on LL. Two regions that were not resolved in the earlier color data are Louisiana, a depression near the neck (23 ± 2% slope), and North Dakota, a linear depression or groove (24 ± 1% slope), labeled in Fig. 1A. Bright material (bm) in the geological map (3) is in some places more and in others less red than average, suggesting that that unit is composed of two or more distinct materials. Another depressed region (dr) on LL is slightly redder than the average (29 ± 2% slope). Some bright spots (sp) appear to have distinct colors as well, although they are not all the same; some are a little redder than average while others are a little less red. The lack of a consistent color pattern for these spots suggests that they may have resulted from delivery of diverse material in impacts rather than by impact excavation of a uniform subsurface material. However, the nature of these spots remains ambiguous (3).

We performed a principal components analysis (PCA) of the color data (Fig. 2). This analysis projects the data into an orthogonal basis set, with the first axis corresponding to the axis of maximum variance within the data. The second axis corresponds to the maximum remaining variance after collapsing the data along the first axis, and so forth. Principal component 1 (PC1, Fig. 2A) corresponds with contrasts between the NIR and CH4 filters and to spectral curvature between BLUE, RED, and NIR filters, respectively. They account for only 1% of the variance between them, much of it due to image noise rather than real color variations across the surface of Arrokoth.

Red coloration on planetary bodies is often attributed to the presence of tholins (19). These are a broad class of refractory macromolecular polymer-like organic solids, commonly produced in laboratory simulations of energetic radiation acting on various combinations of simpler molecules (20–22). The precursors can be in gaseous form (23) or frozen solid (24, 25). Figure 3 compares the color of Arrokoth

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**Fig. 1.** The CA05 color observation of (486958) Arrokoth. (A) LORRI panchromatic context image obtained as a rider during the CA05 observation; the geometry is nearly identical to the MVIC observation, but with a finer spatial scale of 83 m pixel−1. Abbreviations and informal feature names (clockwise from top): SL, smaller lobe; MD, Maryland; LA, Louisiana; dr, depressed region; LL, larger lobe; bm, bright material; ND, North Dakota; sp, bright spots. These features can be seen more clearly in higher-resolution LORRI images [figure 1 of (3)]. (B) Color observation CA05, at a spatial scale of 340 m pixel−1. The BLUE filter (400 to 550 nm) is displayed in blue, RED filter (540 to 700 nm) in green, and NIR filter (780 to 975 nm) in red. (C) Color slope map obtained by fitting a linear model to the BLUE, RED, and NIR reflectance values.
with that of other KBOs and related populations. Arrokoth’s color slope is consistent with other CCKBOs (8). It is less red than the reddest KBOs and the red group of Centaurs (26), whose red coloration is generally interpreted as due to tholins (19). Arrokoth is much more red than the gray Centaurs and various classes of asteroids (27), including the red D-type asteroids that dominate the Jupiter Trojan population (28). Using the Sloan $g$, $r$, and $z$ filters, KBO colors can be placed on a color-color plot of $g-r$ and $r-z$ color differences, which has revealed a distinction between CCKBOs and more dynamically excited KBO populations (8). The latter appear to follow two color tracks (29) (Fig. 3B) while the CCKBOs cluster below and to the right, owing to their red slopes becoming less steep at $z$-band wavelengths (0.82 to 0.96 μm). Arrokoth’s red slope continues into MVIC’s NIR band (0.78 to 1 μm). After converting to Sloan colors, Arrokoth lies above the main clump of CCKBO colors in Fig. 3B, although this is consistent with the overall CCKBO color distribution.

Near-infrared spectral reflectance

The LEISA data were processed into a spectral cube, with spatial dimensions along two axes and wavelength along the third axis (15). The cube-building algorithm we adopted accounts for changes in spacecraft range over the course of the CA04 LEISA scan [unlike (1)]. The spatial resolution of the LEISA data is considerably coarser than that of the corresponding LORRI ride (Fig. 4), and the signal/noise ratio is considerably lower. Noise in the LEISA data is dominated by instrumental effects, which are as large as the signal from sunlit areas on Arrokoth, so spectral features can only be revealed by averaging over multiple pixels and/or wavelengths. The spatially averaged spectrum (Fig. 4C) lacks the strong absorption features that were seen in the Pluto system [e.g., (30)]. The red color slope seen in the visible flattens with increasing wavelength to become neutral by ~1.5 μm. We constructed Hapke reflectance models (15, 31) for various combinations of potential surface components. The data support inclusion of amorphous carbon and tholins in the models. Combinations of these materials match the overall albedo and spectral shape. Although we used tholins made in conditions simulating the atmosphere of the moon Titan (20), the data do not support singling out any of the various tholins with published optical constants. None have been made under simulated outer nebular conditions, so they may not be particularly good analogs for the tholins on Arrokoth. Amorphous carbon has no diagnostic spectral features in this wavelength...
range, so it cannot be specifically identified. Any dark, spectrally neutral material would be equally consistent with the data.

Shallow absorption bands can be discerned near 1.5 to 1.6 μm, 1.8 μm, 2.0 to 2.1 μm, 2.27 μm, and 2.34 μm (Fig. 4C). Inclusion of ices of methanol (CH₃OH), water (H₂O), and ammonia (NH₃) enables the models to match many of these features, but not the one at 1.8 μm. With the low signal/noise ratio of the LEISA spectrum, even in the global average, we must consider the information content and limit the model free parameters to those that can be statistically justified. Of the molecular ices we tried, only the addition of CH₃OH produces a sufficiently large improvement in χ² to constitute a confident detection (15). This does not preclude the presence of H₂O or NH₃ ices, but the available data do not provide statistically significant evidence for their presence. Adding more than a trace of them to the models makes χ² worse, but the increase can be minimized with large grain sizes that limit the projected area of H₂O or NH₃ grains to a small fraction of the total. Small amounts of other ices, such as H₂CO, CO₂, or C₃H₆, could also be compatible with the data, as could the silicate and metallic phases that have been seen in comets and interplanetary dust particles. The 1.8-μm feature in Arrokoth’s spectrum is not matched by available ices or tholins and remains unidentified. It could be an artifact.

To search for spectral contrasts across the surface of Arrokoth, we selected several regions of interest (ROIs), as shown in Fig. 4B. These include LL, the brighter neck region (n), and a pair of ROIs on the left and right sides of SL: sr, which incorporates the redder material on the rim of Maryland, and sl, which represents portions of SL unrelated to Maryland. Spectra of these regions are shown in Fig. 4C. In averaging over fewer pixels, the signal/noise ratios in the ROI spectra are correspondingly poorer than the global average. However, the ROI spectra all look very similar to the average, and fitting Hapke models shows that tholin, carbon, and CH₃OH are favored, without statistically significant evidence for H₂O or NH₃ ices, just as with the average.

Our confidence in the detection of CH₃OH is increased by the appearance of two distinct absorption bands of methanol ice: one band at 2.271 μm, attributed to (v₁ + ν₁₁) or (v₁ + ν₂) vibrational combination modes, and another at 2.338 μm, attributed to (v₁ + ν₆) (32). These spectral characteristics have been seen in Earth-based spectra of the Centaur 5145 Pholus (33) and the resonant KBO (55638) 2002 VB₁₉ (34). Additional, weaker CH₃OH absorption bands at 1.6 and 2.1 μm are not visible in Arrokoth’s spectrum. In the case of Pholus, the spectrum from 0.45 to 2.45 μm was fitted with a radiative transfer model incorporating solid CH₃OH and H₂O, in addition to an iron-bearing olivine (forsterite Fo 82) and tholin (33), similar to our models for Arrokoth, except that H₂O ice is not required in the Arrokoth models.

To assess spectral contrasts in a way that does not depend on multiple scattering models, we performed a PCA on the LEISA cube, with results shown in Fig. 5. Because of the low signal/noise ratio, we first binned the wavelengths down to 28 channels, producing an effective spectral resolving power of 39. We also discarded pixels along the edge where jitter during the scan is prone to producing artifacts. As with the MVIC colors, PC1 is sensitive to the overall light variation from shading and albedo, with the eigenvector flat across all wavelengths (Fig. 5A). PC1 accounts for 72% of the total variance in the LEISA data. PC2 captures only 2.3% of the variance, but the eigenvector shows pronounced dips around 1.5 and 2 μm, where H₂O ice has its strongest absorption bands within LEISA’s spectral range; this finding suggests that regional variations in H₂O ice absorption could be the next most prominent source of spectral variance across the surface of Arrokoth, perhaps being most abundant around Maryland crater. However, the absence of strong H₂O absorptions in any of our extracted spectra (including the sr ROI that covers this region) reduces confidence in that conclusion. Subsequent PCs account for even lower fractions of the total variance. The lack of spatial coherence in the images, coupled with eigenvectors that are not suggestive of absorption by likely surface constituents, suggests that the higher PCs are responding mostly to instrumental noise rather than to signal in the LEISA data.

**Thermal environment**

The CA03 REX observation was performed on approach, observing Arrokoth’s day side; the CA08 observation was done after closest approach, looking back at Arrokoth’s night side. The microwave sky background is shown in Fig. 6A (35, 36). The CA03 observation was performed with a fixed staring geometry. A later observation of the same field was obtained for background subtraction, but the system antenna temperature drifted over time, making it difficult to separate out the flux from Arrokoth. The CA08 night-side observation was obtained under more favorable geometry, from a closer range, and with the antenna scanned along the uncertainty ellipse for Arrokoth’s location. Scanning instead of staring facilitated calibration against the later background observation despite the drift in system response. The flux measurements are shown Fig. 6B. The radiometric signal was converted to radio brightness temperature.
using procedures developed earlier in the mission, accounting for the solid angle subtended by Arrokoth within the antenna beam (15, 17, 36, 37). Accounting for the 414.4-km² cross section of Arrokoth and noise from instrument and background, we obtain a mean brightness temperature \( T_B \), averaged across the night-side visible face of Arrokoth, of \( T_B = 29 \pm 5 \) K, which is within the range of brightness temperatures estimated from an earlier analysis (1). To translate that brightness temperature to a kinetic temperature requires knowledge of the X-band emissivity of Arrokoth’s surface, which is not known but most likely lies in the range 0.7 to 0.9 (36).

Thermophysical models were used to assess the implications of this \( T_B \) measurement (15). For each surface element of the three-dimensional (3D) shape model (3), we balanced radiative losses and thermal conduction against insolation (received sunlight) and also reradiation from other parts of Arrokoth’s surface visible from that location. Accounting for self-shadowing and surface reradiation makes this modeling inherently global in scope (38). Subsurface thermal evolution was simulated with a 1D thermal diffusion prescription (15). For simplicity, we assume that Arrokoth’s obliquity does not precess and that its orbit is circular, with a semimajor axis of 44.2 AU and period of 298 years. At this distance, the incident solar radiation flux \( F_\odot \) is 0.7 W m⁻². Given Arrokoth’s 99.3° obliquity (2), seasonal effects are strong. We determined the subsolar latitude along approximately 300 equally spaced temporal nodes over one orbital period (15). During the New Horizons flyby, the subsolar latitude was approximately −62°. At each orbital node, the daily averaged (15.9-hour period) solar insolation was calculated, accounting for self-shadowing. With these diurnally averaged insolation profiles, we determined the surface temperature on every element over the course of an orbit. We assumed that the subsurface thermal response is in the time-asymptotic limit, meaning there is no net gain or loss of thermal energy into or out of the interior over the course of one orbit (39). This assumption requires heat from radioactive decay inside Arrokoth to be negligible and requires the interior to have reached thermal equilibrium with the Sun over the course of the lifetime of the Solar System (see below).

We assume that the low–bond albedo \( A_B = 0.06 \) (1, 3) surface of Arrokoth is characterized by a very low thermal inertia \( (\Gamma = 2.5 \) J m⁻² s⁻¹/² K⁻¹) typical of loosely consolidated granular material, as inferred from infrared observations of KBOs (40). The thermal inertia is given by \( \Gamma = \sqrt{k p C_p} \), where \( k \) is thermal conductivity, \( p \) is density, and \( C_p \) is specific heat at constant pressure. Arrokoth’s bulk density must be at least 290 kg m⁻³ and densities of small KBOs and comet nuclei tend to be higher than that, but generally less than 1000 kg m⁻³ (41, 42). The density near the surface that matters for Arrokoth’s thermal response is even more uncertain and could differ substantially from the bulk density. We assume a generic density of \( p = 500 \) kg m⁻³ (3) and that \( C_p = 350 \) J kg⁻¹ K⁻¹. Under these assumptions, the corresponding thermal conductivity is \( 3.6 \times 10^{-5} \) W m⁻¹ K⁻¹, very low relative to values determined for surfaces in the inner Solar System. These values correspond to a seasonal thermal skin depth \( \lambda = 0.55 \) m, where \( \lambda = \sqrt{k/\epsilon \rho C_p} (\rho C_p 2\pi) \) and \( \tau_s \) is the 298-year seasonal period (43). This value is similar to the electrical skin depth (36). The subsolar equilibrium temperature \( T_s = 58 \) K was obtained from \( \sigma T_s^4 = (1 - A_B) F_\odot \), where \( \sigma \) is emissivity [commonly assumed to be 0.9; e.g., (40, 43)], \( \sigma \) is the Stefan-Boltzmann constant \( (5.67 \times 10^{-8} \) W m⁻² K⁻⁴, and \( F_\odot \) is the solar flux at 44.2 AU. The thermal parameter \( \Theta = \Gamma \kappa \alpha^{-1/2} \) characterizes the efficiency of the energy transport rate (per K) of thermal conduction across one seasonal skin depth relative to radiative losses (43), which is about \( \Theta = 0.02 \) for Arrokoth. Such a small value of \( \Theta \) indicates that the surface layers are highly insulating, leading to extreme variations in surface temperature over the course of a year. Winter surface temperatures are much lower than peak summer temperatures. The low conductivity might only pertain to a surficial layer. If deeper below the surface the texture is more compacted with greater granular contact, the conductivity would likely be higher. We can estimate the body’s thermalization time scale by calculating the thermal wave propagation time \( (\tau_{\text{thermalization}} = 2pC_p R^2 \kappa^{-1}) \) across a length scale \( R \) corresponding to the characteristic radius of the short axes of both lobes (≈3.5 km). For values of \( k \) greater than \( 10^{-4} \) W m⁻¹ K⁻¹, this time scale is less than the age of the Solar System, supporting our assumption of a time-asymptotic state.

Figure 7A shows the insolation averaged over an orbit from two viewing positions. The flattened shape and high obliquity lead to the equator receiving less energy on average (≈0.1 W m⁻²) than the poles (≈0.2 W m⁻²). Owing to self-shadowing, the neck region generally receives less energy than the equatorial zone (ranging from 0.06 to 0.08 W m⁻²). Figure 7B shows the additional radiation received from thermal emission from other parts of Arrokoth itself, again averaged over an orbit. Our model indicates that the neck region is warmed by this trapping process, receiving about 0.025 to 0.04 W m⁻² from self-radiation, which partially offsets the effect of shadowing. Figure 7C shows the orbital average of the warming due to self-radiation. The neck region experiences the greatest amount of relative warming, in the range of −1 to 3 K. Maryland crater also receives enhanced thermal reradiation, but the relative warming in
that region is slight, about 0.5 K. Figure 7D shows the predicted observable surface temperature at the time of the New Horizons encounter. Typical temperatures are in the range of 50 to 57 K near the poles of each lobe, falling to ~40 K near the equator. Parts of the neck region that are not shaded at times of high subsolar latitude (~62° at the time of the encounter) stand out as having among the warmest surface temperatures during the encounter, as high as 60 K.

Figure 7E shows the predicted surface temperature at the time and viewing geometry of the CA08 REX observation, during which the sub-spacecraft point was latitude +44°, longitude 78°E. From this orientation, the model shows the predicted observable surface temperature at the time of the New Horizons encounter: Typical temperatures are in the range of 50 to 55 K near the poles of each lobe, falling to ~40 K near the equator. Parts of the neck region that are not shaded at times of high subsolar latitude (~62° at the time of the encounter) stand out as having among the warmest surface temperatures during the encounter, as high as 60 K.

**Implications for formation**

The distribution of orbits in the present-day Kuiper belt was strongly influenced by an outward migration of Neptune early in Solar System history, resulting from dynamical interaction between Neptune and the disk of planetesimals [e.g., (44)]. Neptune's migration stopped at 30 AU from the Sun, indicating a break in the distribution of planetesimals in the disk, beyond which there was insufficient mass to drive Neptune's migration further outward (45). Most KBOs that have been studied spectroscopically [e.g., (46, 47)] are not CCKBOs; they originated in the denser planetesimal disk from inside 30 AU. Likewise, most comets that approach the Sun and Earth, and therefore can be studied in detail, likely do not sample the outer planetesimal disk from beyond 30 AU. Arrokoth may contain a record of conditions in the outer part of the nebula where it formed. Constraints include the evidence for methanol ice and the lack of evidence for water ice, which is unlike the high abundance of H₂O in many outer Solar System bodies and interstellar grains.

CCKBOs appear to have formed in the outer solar nebula through the gravitational collapse of pebble-size particles, concentrated aerodynamically (13, 48). In this scenario, microscopic dust grains coagulate into larger particles (49, 50). As particles approach pebble sizes, they decouple from the gas, causing them to spend most of their time near the cold disk midplane and allowing them to become concentrated in dense clumps that can gravitationally collapse into planetesimals (51, 52). The (original) bulk composition of CCKBOs should reflect the makeup of the solids present in the midplane of the solar nebula at the time and location of their formation. It remains unclear, however, how long the dust coagulation phase lasted and/or how far pebbles were able to move radially inward [e.g., (53)] before they formed planetesimals.

When the solar nebula formed, the chemical composition of the ices present in the outer regions was set by a combination of inheritance from the parent molecular cloud and chemistry taking place during formation of the disk. In the midplane of the outer disk, the resulting CH₃OH/H₂O ratio on cold grain surfaces likely did not exceed a few percent (54). During the subsequent disk evolution, spatial variations in physical conditions such as temperature, density, and radiation environment, coupled with ongoing chemistry (55) and transport or mixing processes (56), result in gas-phase and ice compositions changing over time.

In regions where it was cold enough for highly volatile CO to freeze as ice onto grains (57), methanol could be formed through successive addition of hydrogen atoms to CO ice. Both interstellar and outer nebular environments are potential settings for this chemistry (58–60). Before the loss of nebular gas and dust, the midplane of the disk was shaded from direct sunlight and extremely cold, favoring condensation of CO in its outermost
portions. Simulations of protoplanetary disks indicate that methanol can be produced in this way (consuming CO) on time scales of \( \sim 1 \) million years at Arrokoth from the Sun (61). Intermediate steps include formation of formaldehyde (H2CO) and radicals (e.g., CH3O). Radiolytic destruction of CH3OH can produce H2CO, but the band at 2.27 \( \mu \)m remains prominent even after irradiation (62).

Another potential CH3OH formation mechanism involves radiolysis of mixed H2O and CH4 ices (63–66). Again, low temperatures consistent with the shaded midplane are required for CH4 to be frozen onto grains, although CH4 is not quite as volatile as CO. If such radiolytic production occurs with an excess of CH4, the H2O could be consumed, providing a possible explanation for the lack of evidence for H2O at Arrokoth. Such a radiolytic process would also efficiently form simple hydrocarbons such as C2H4 and C2H6, which are known to be precursors of complex organic tholins [e.g., (20, 67)].

Gas-phase methanol has been detected at low abundance in protoplanetary disks around nearby stars (68). This is consistent with methanol ice formation on grain surfaces, with a small fraction subsequently released to the gas through nonthermal desorption mechanisms [e.g., (60, 69)]. This would also be consistent with the observation that many of these disks are also depleted in gaseous CO (70, 71), requiring a combination of sequestration on pebbles and chemical processing (61, 72, 73).

Although H2O was not detected on Arrokoth, it could be present but somehow masked or hidden from view, such as by materials produced through radiolysis or photolysis of CH3OH ice and perhaps other undetected precursor materials. Preferential removal of H2O ice from the uppermost surface by a process such as sputtering is another possibility, although it is unclear that H2O should be more susceptible to such removal than CH3OH is. Spectra of some larger KBOs also lack H2O absorption features (46, 47). H2O ice absorption is considerably weaker in the spectrum of Arrokoth than seen on Pholus and (55638) 2002 VE95, the two other objects with strong CH3OH signatures, but those objects are much larger than Arrokoth (74, 75). They likely formed in the closer, more densely populated planetesimal disk originally inside 30 AU, as did other, large KBOs where strong H2O ice signatures have been detected spectroscopically. It is hard to envision a mechanism that preferentially masks or removes H2O from the surface of Arrokoth but not the H2O on these other objects. Their contrasting compositions suggest that the observed surface composition of these bodies is reflective of their bulk compositions, and that Arrokoth’s composition is...
distinct from those of planetesimals that formed closer to the Sun. A contrast in planetesimal composition driven by nebular chemistry enabled by CO and/or CH$_4$ frozen on grains may be connected to the transition at 30 AU that halted Neptune’s outward migration at that distance.

Although regional variations in tholin and ice abundance could cause albedo, color, and spectral variations, the subtle variations that are seen at Arrokoth do not require compositional differences. Reflectance also depends on mechanical properties such as particle size distribution and degree of compaction (31). The merger of the two lobes (13) could have mechanically modified the material in the neck region. After the formation of Arrokoth from the nebula, low-speed impacts of residual debris could locally modify surface textures, which might account for some of the spots with slightly contrasting colors and albedos.

**Surface and interior evolution**

The surface features of comets are dominated by geologically rapid volatile loss and sublimation erosion, whereas the surfaces of larger asteroids are dominated by high-energy impacts. In contrast, Arrokoth and the CCKBOs are distinct in inhabiting an environment with very little energy input from interstellar, solar, and micrometeorite sources that require long time scales to modify the surface. Depending on the thermal parameters, surface temperatures range from as low as 10 to 20 K in winter to 50 to 60 K in summer, with the neck region getting at most a few degrees warmer than the rest of the surface. Subsequent to the loss of shading and subsequent warming, the surface should accumulate a lag deposit enriched in more refractory materials through loss or destruction of more volatile and fragile molecules.

It is not obvious from the encounter data whether a distinct surface veneer exists on Arrokoth. Albedo and color contrasts corresponding to ancient features such as the neck suggest that such contrasts are not quickly masked by a space weathering processes. If compositionally distinct interior material was exposed at the neck, it might weather differently and thus maintain a contrasting appearance, but the LEISA data show no evidence for a distinct composition in the neck region. The warmer thermal environment of the neck would be another potential reason for distinct evolution there, but the temperature difference is too small to produce outcomes that differ substantially from the rest of the surface.

No obviously fresh craters expose distinct-looking interior material (with the possible exception of Maryland), and color trends do not appear to correspond to downslope transport, which is generally from equators to the poles of the lobes, and ultimately to the neck (3). Less-altered interior material should be preferentially exposed at high elevations, but we do not observe obvious color differences in high-standing regions along the equators. Brighter material in the neck and in Maryland may accumulate in topographic lows, suggestive of textural rather than compositional contrasts. Among the CCKBO population, the diversity of colors coupled with similar colors of different sized components of binaries have been used to argue against the importance of size-dependent factors such as the balance between erosion and space weathering in altering their surface colors (82).

The evolution of Arrokoth’s interior is shaped by energy inputs that are even smaller than at its surface. Subsequent to the loss of shading from nebular dust, insolation would have raised Arrokoth’s equilibrium temperature. As that thermal wave slowly propagated inward, highly volatile species such as N$_2$, CO, and CH$_4$ would have become unstable, at least as condensed ices. Early outgassing of these species may have produced what appear to be collapse or outgassing pits at the boundaries of terrain units (1, 3). Such features may be analogous to pits or sinkholes on comet 67P/Churyumov-Gerasimenko [e.g., (83, 84)]. Localization of the pits to certain regions may arise from variable permeability of surface deposits that would favor volatiles escaping through weaker zones at unit boundaries. However, the equilibrium temperature in Arrokoth’s interior never would have been high enough for amorphous ice to crystallize and expel its payload of trapped volatiles [e.g., (85, 86)]. Apart from loss of these volatile species, Arrokoth’s interior may have undergone little alteration or processing since accretion, and could thus preserve many characteristics of the original accretion such as layering [as observed on comets (87, 88)], very high porosity, and an intimate mixture of nebular ices, organics, and silicate dust grains.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Fig. S1

Data S1

References (89–98)

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