Ultima Thule (486958; 2014 MU69): Necklace, Composition, Rotation, Formation

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ABSTRACT

Flyby images of Ultima Thule (486958; 2014 MU69) show a comparatively bright “necklace” between its two lobes, in contrast to its generally low albedo. The necklace is found in the most shaded, and therefore coolest, part of its surface. It may be clean, high albedo, “hoarfrost” condensed from vapor evaporated from the low albedo dirty ice elsewhere. Ammonia, the likely major constituent of Ultima Thule, has the necessary vapor pressure. The rotation period of 15 ± 1 h is at least twice its breakup period, indicating either that its formation was not limited by angular momentum or that half its angular momentum was lost after formation, perhaps to surrounding gas in the proto-Solar System. The lobes of Ultima Thule must have spherized under conditions different than those encountered by its present, post-contact, configuration.

Key words: Kuiper Belt Objects: Ultima Thule

1 INTRODUCTION

Ultima Thule (Stern et al. 2019), a classical Kuiper belt object, became the most distant object visited by a spacecraft following the flyby by New Horizons January 1, 2019. Imaging revealed it to be a contact binary consisting of two roughly spherical lobes with diameters of 19.5 and 14.2 km, rotating with a period of 15 ± 1 h. Its visible light albedo $A \approx 0.1$. Its location in the outer Solar System with orbital semi-major axis $a = 44.24$ AU and eccentricity $e = 0.038$ (Porter et al. 2018) suggests a predominantly icy composition, although its low albedo implies some mineral (“dirt”) admixture with the mineral matter welded into a continuous icy matrix 1.

The most striking feature of images of Ultima Thule is a bright ring or “necklace” where the two lobes are in contact. This paper proposes that the necklace is produced by thermal evaporation of ammonia ice from the most strongly heated portions of the surface and the deposition of some fraction of it on the neck, the most shaded and coolest portion. Deposition from the vapor would produce a layer of nearly pure solid ammonia, with the high albedo of a snowbank or hoarfrost. Brighter regions in other surface depressions may have a similar origin.

The peculiar shape of Ultima Thule, consisting of two roughly spherical lobes in contact, a far from spherical configuration, rotating at about half their break-up rate, also requires explanation: Why did the process that spherized the lobes not spherize the present configuration? This paper proposes that the lobes formed and spherized in the proto-Solar System, perhaps when the Sun was on its Hayashi track and Ultima Thule was warmer and the proto-Solar System was filled with gas. Bodies immersed in gas that prevents the free escape of evaporated material spherize by evaporation from the convex and warmest parts of their Solar-heated surfaces and recondensation on cooler, shadowed, concave parts. When the Solar luminosity decreased as it moved down the Hayashi track this process slowed, but gas drag could still bring the lobes together and slow the rotation of the resulting contact binary.

2 HEAT FLOW

With the Sun overhead, the steady state surface gray-body temperature at sub-Solar points $T_{\text{max}} = (I_{\odot}/\sigma_{SB})^{1/4}$, where
\( I_\odot \) is the Solar intensity and \( \sigma_{SB} \) the Stefan-Boltzmann constant, varies around the orbit from 58.4 K to 60.6 K. The deep interior of a gray-body sphere comes to the mean temperature \( (T) = (I_\odot/\sigma_{SB})^{1/4} \approx 42 \text{ K} \), and shadowed surfaces are much colder, heated only by thermal conduction. At earlier times in the main sequence history of the Sun it was less luminous, so that Ultima Thule was colder, but when the proto-Sun was on its Hayashi track it was more luminous than today, so that if Ultima Thule had formed then it would have been significantly warmer than it is today.

The far-IR emissivity of solid NH\(_3\) is uncertain (the thermal radiation peaks at wave numbers \( \sim 200 \text{ cm}^{-1} \), much greater than molecular rotational level spacings but much less than the vibrational level spacings of small molecules) so these estimates can only be approximations to the actual surface temperature. If the far-IR emissivity is unity the temperature is less by a factor of \( (1 - \alpha)^{1/4} \approx 0.97 \), but Ultima Thule could be significantly warmer if its far-IR infrared emissivity is smaller.

For an object of size \( r \), thermal conductivity \( K \), and radiatively heated temperature \( T \) that varies by \( \Delta T \) across its surface the ratio of conductive heat flow in steady state from the warmest part of the surface to its black body radiation is

\[
\frac{F_{\text{conduct}}}{F_{\text{rad}}} \approx \frac{K \Delta T}{\sigma_{SB} R^2} \sim 10^{-2},
\]

where the thermal conductivity of solid ammonia at \( T = 40-60 \text{ K} \) \( K \approx 5 \times 10^5 \text{ erg/(cm-s-K)} \) (Krupskii, Manzhely & Koloskova 1968) and we take \( T = 60 \text{ K}, \Delta T = T_{\text{max}} - (T) = 18 \text{ K} \) and \( r = 10 \text{ km} \).

Thermal conduction is a minor contributor to the steady state thermal balance of sunlit surfaces.

However, the surface of Ultima Thule is not in steady state because it rotates and the Solar direction changes through its orbit. Its rotation axis appears to be near its orbital plane, so that some portions of its surface are sunlit for \( \sim 100 \text{ y} \) of its orbital period of 294 y. During transient heating reradiation competes with conductive heat flow into the interior as a sink of absorbed energy. In a time \( \Delta t \) the thermal diffusion wave penetrates a distance \( \Delta x \approx \sqrt{K \Delta t/(C_{p,s} \rho)} \), where \( C_{p,s} \) is the heat capacity (per unit mass) of the solid, carrying an energy per unit area \( C_{p,s} \rho \Delta T \Delta x \), while the surface absorbs \( I_\odot \Delta t \). Taking \( C_{p,s} \) from Popov, Manzheli & Bagatskii (1971) and comparing these energies indicates that the steady state approximation is only valid for

\[
\Delta t \gg \frac{(\Delta T)^2 C_{p,s} \rho K}{I_\odot^2} \approx 1.5 \times 10^9 \text{ s} \approx 50 \text{ y}.
\]

This condition is at most barely met. The actual peak surface temperature is \( \approx 50 \text{ K} \), between \( T_{\text{max}} \) and \( (T) \), and depends on unknown details of the shape and orientation of Ultima Thule in addition to its infrared emissivity.

### 3 VAPOR PRESSURES

Even at the low temperatures of Ultima Thule, the volatiles He, H\(_2\), CO, N\(_2\), O\(_2\), CH\(_4\), C\(_2\)H\(_6\) and possibly CO\(_2\) are rapidly lost. The escape velocity \( v_{\text{esc}} \approx 6 \text{ m/s} \) if it is made of ammonia or water ice \( (v_{\text{esc}} \approx 8 \text{ m/s} \) if made of CO\(_2\)) far below the thermal velocity of any light molecule \( (v_{\text{th}} \approx 150-200 \text{ m/s}, \) depending on molecular weight, at 60 K), so gravity does not much slow their escape. The vapor pressures of molecules of possible interest are shown in Fig. 1.

Vapor pressures are calculated from the triple point pressures and the Clausius-Clapeyron equation with one component a perfect gas:

\[
d\ln P_{\text{vap}} = \frac{L(T)}{k_B T^2},
\]

where \( L(T) \) is the latent heat of the phase transition. Not all the required \( L(T) \) are available (in particular for NH\(_3\) hydrate, which I do not consider explicitly). For NH\(_3\) it is necessary to extrapolate the latent heat of vaporization of liquid NH\(_3\) from 214.2 K, the lowest temperature for which data are available (Osborne & Van Dusen 1918), to its triple point of 195.4 K. The result is \( 350 \pm 5 \text{ Cal/g} = (4.14 \pm 0.06) \times 10^{-13} \text{ erg/molecule} \), where both the value and its uncertainty are estimated by graphical extrapolation.

The latent heat of sublimation of the solid at the triple point is the sum of the latent heat of melting and that of evaporation of the liquid, and hence \( L(T) \) is discontinuous at a triple point. This produces small discontinuities in the slopes of the curves in Fig. 1.

When the latent heat is not directly measured (such as at temperatures below the triple point where the vapor pressure is small), it is obtained from the latent heat at a temperature where it is known, typically the triple point, using

\[
d\ln P_{\text{vap}} = C_{p,g} - C_{p,s}.
\]

The specific heat of NH\(_3\) vapor, \( C_{p,g} \approx 4k_B \) per molecule, is that of a classical gas with three rotational but no vibrational degrees of freedom because the rotation constants are, in temperature units, 14.3 K and 8.9 K (Benedict & Plyler 1957), sufficiently below the temperatures of interest. The inversion level spacing of 1.14 K (Popov, Manzheli & Bagatskii 1971) contributes negligibly to the specific heat.

The corrections to \( L(T) \) contributed by Eq. 4 amount to only a few percent, and change sign around \( T = 129 \text{ K} \) so their effects on the vapor pressure at \( \sim 60 \text{ K} \) approximately cancel. This small correction is made for the molecule of greatest interest, NH\(_3\), but not for the others (for most of them correction would not be possible because the specific heats of their solids are not available).

### 4 EVAPORATION RATE

A surface (of a single material) evaporating into vacuum loses material at a rate (molecules per unit area per unit time)

\[
N = \alpha n_{\text{vap}} v_{\text{th}},
\]

where \( n_{\text{vap}} \) is the equilibrium vapor density, \( v_{\text{th}} \) is its thermal velocity and \( \alpha \) is, by detailed balance, the sticking probability of a vapor molecule striking the surface. We adopt \( \alpha = 1 \),
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Figure 1. Vapor pressures of several substances of interest. Curves are in the same order, top to bottom, as the key. The vertical lines indicate $T_{\text{max}} = 59.5 \text{ K}$, the mean (over the orbit) grey-body steady state sub-solar (maximum) temperature and $(T) = 42 \text{ K}$, the deep interior temperature. Vapor pressures above $P_{\text{max}}$ would lead to evaporation of an object the size of Ultima Thule in the age of the Solar System. Vapor pressures below the geometry-dependent $P_{\text{min}}$ could not produce a layer of high albedo “hoarfrost”; these vapor pressures are shown for NH$_3$ but depend slightly on molecular weight. This condition is much less demanding for concave surfaces, such as those showing high albedo in Ultima Thule, than for convex surfaces. CO$_2$ is unlikely to be retained to the present day (see discussion in text) and CH$_3$OH and H$_2$O are unlikely to provide enough evaporation and redeposition to make the observed regions of high albedo. The narrow wedge for NH$_3$ corresponds to the estimated range of uncertainty in the extrapolation of its latent heat (see text); this is much less important than the uncertainty in the surface temperature. NH$_3$, HCN and C$_3$H$_8$ could evaporate and condense as hoarfrost on shaded surfaces; of these, NH$_3$ is likely to be the most abundant. Triple points, where the inclusion of the latent heat of melting produces small discontinuities in slope, are indicated by dots; when not shown they are outside the range of the plot.

Figure 2. Thermal evaporation from Solar heated convex (above) and concave (below) surfaces. Dotted arrows indicate direction of incident sunlight, and dashed arrows the paths of evaporated molecules. Redeposition is efficient on concave surfaces, such as the neck between the lobes of Ultima Thule and in depressions or pits, even if the molecules are moving faster than escape speed, as almost all of them do.

If

$$v_{\text{recession}} > v_{\text{max}} \sim \frac{\rho}{t_{SS}} \sim 10^{-11} \text{ cm/s},$$

(9)

where $t_{SS} = 1.4 \times 10^{17} \text{ s}$ is the age of the Solar System, an object the size of Ultima Thule evaporates in time $t_{SS}$. This corresponds to maximum vapor pressure at 60 K of $P_{\text{max}} \sim 10^{-7} \text{ dyn/cm}^2$ (scaling $\propto T^{3/2}$).

The vapor pressure of CO$_2$ is probably too high for it to be retained for the age $T_{SS}$ of the Solar System because a significant fraction of the surface of Ultima Thule may be at temperatures above 50 K (at 55 K a 10 km thickness would evaporate in 0.01$t_{SS}$). It is also evident that the vapor pressures of H$_2$O and CH$_3$OH are too low to provide sufficient evaporation to deposit a high albedo hoarfrost.

5 DEPOSITION

A minimum recession rate $v_{\text{min}}$ is required for sufficient material to be evaporated to coat the cooler shaded parts of the body, such as the neck between its lobes and the insides of depressions, and increase their albedo, in a time $t_{SS}$. This hoarfrost of pure ice (probably ammonia ice) will have a high visible albedo if its thickness is $\geq 0.1\lambda$, where $\lambda$ is the wavelength of Solar radiation.

The required minimum recession rate

$$v_{\text{recess}} > v_{\text{min}} \sim \frac{0.1\lambda}{t_{SS}} \sim 3 \times 10^{-23} \epsilon^{-1} \text{ cm/s},$$

(10)

where $\epsilon$ is the fraction of evaporated material that is deposited on colder parts of the surface as “hoarfrost”. Two cases need consideration.
5.1 Convex Surfaces

If the surface is convex, only evaporated molecules that have less than escape velocity can contact colder parts of the surface and be redeposited, as shown in the upper part of Fig. 2. Because \( v_{esc} \ll v_{th} \), a fraction \( \epsilon \sim (v_{esc}/v_{th})^3 \) \( \sim 3 \times 10^{-5} \) (NH3) or \( \sim 1 \times 10^{-4} \) (CO2) of the evaporated matter remains gravitationally bound. Only these low velocity molecules, moving ballistically (the vapor density is so low that collisions between molecules are rare), will strike the surface again. Then for NH3

\[
P_{\text{evap}} > \frac{0.1 \kappa_{\text{sat}} k T}{C_{\text{SS}} v_{th}} \sim 1.5 \times 10^{-14} \text{ dyne/cm}^2; \tag{11}
\]

for CO2 the required \( P_{\text{evap}} \) is about 2.5 times less.

5.2 Concave Surfaces

The neck between the two lobes of Ultima Thule is concave, as are the insides of depressions, and molecules evaporated from the warmer parts of the surface may directly strike colder parts, even though their velocities exceed \( v_{esc} \). This is illustrated in the lower part of Fig. 2. Then \( \epsilon \) may be much higher, perhaps \( O(0.1) \), and

\[
P_{\text{evap}} > 3 \times 10^{-18} \text{ dyne/cm}^2. \tag{12}
\]

5.3 Net Deposition

Both the warmer and the cooler parts of the surface will evaporate, but the cooler parts will be net gainers of ice if their evaporation rate is \( \epsilon \) of the evaporation rate of the warmer parts. This condition will be satisfied if \( \Delta T > \Delta T_{\text{min}} \), where

\[
\Delta T_{\text{min}} \approx -\frac{d \ln \epsilon}{d \ln P_{\text{evap}}/dT}; \tag{13}
\]

for NH3 at 50 K \( d \ln P_{\text{evap}}/dT = L/k_B T^2 \approx 1.5/K \).

For a convex surface \( \Delta T_{\text{min}} \approx 7 \text{ K} \). The temperature difference between unshadowed and shadowed parts of the surface likely exceeds this because the mean temperature is 42 K, about 10 K below the sub-Solar temperature. For a concave surface \( \Delta T \) as small as \( O(1 \text{ K}) \) is sufficient.

6 ROTATION

The rotation period of Ultima Thule is 15 ± 1 hours (Stern et al. 2019). The orbital period of two homogeneous spheres of density \( \rho \) in contact is

\[
P_{\text{breakup}} = \frac{3 \pi (1 + \zeta)^3}{G \rho} \frac{1}{1 + \zeta} \approx 7.1 \text{ h}, \tag{14}
\]

where \( \zeta = 0.74 \) is the ratio of the radius of the smaller sphere to that of the larger sphere and the density \( \rho = 0.82 \text{ g/cm}^3 \) of solid NH3 is assumed. \( P_{\text{breakup}} \) is the shortest possible rotation period of a strengthless contact binary, and is about half the observed rotation period, implying that a repulsive force is exerted at their contact. Other possible constituents have densities either close to that of solid ammonia (hydrocarbons are slightly less dense) or are denser (CO2 is 1.6 g/cm3), and have nearly the same or shorter \( P_{\text{breakup}} \); the observed rotation period is at least a factor of two greater than \( P_{\text{breakup}} \) for any possible composition.

The shape of Ultima Thule is that of two spheres brought into contact. It does not conform to the equipotential (Roche) surfaces of a uniformly rotating fluid with mass concentrated at two orbiting points, in which each lobe is drawn to a singularity at their contact. Nor does it resemble the highly prolate (Jacobi ellipsoid) shape of homogeneous self-gravitating bodies of high angular momentum in equilibrium, such as inferred for ‘Oumuamua (Meech et al. 2017; Katz 2018). Nor does it resemble the oblate McLaughlin spheroids of lower angular momentum. This argues against formation models in which a single object was formed by angular momentum-limited accretion (as in an accretion disc like those observed in mass-transfer binary stars) from surrounding gas or particles.

This suggests that the two lobes formed independently as slowly rotating (slower than their breakup rotation rate) spheres because they are not obviously aspherical. Orbiting but separated, their orbit gradually contracted as it lost angular momentum until they came into contact. The long rotation period suggests that some process continued to remove angular momentum after Ultima Thule formed, likely the same process that also brought its lobes together by removing angular momentum (otherwise, some mechanism would be required to end that process and begin another).

A plausible mechanism for removing angular momentum is hydrodynamic interaction with surrounding gas of density \( \rho_g \) in the proto-Solar System. Hydrodynamic interaction produces a characteristic torque \( \sim \rho_g v^2 r^3 \sim GM_{UT} \rho_g r^3 \), where \( r \) is the radius of Ultima Thule and the velocity of its lobes through the gas \( v \sim \sqrt{GM_{UT}/r} \). Gravitational interaction has a similar characteristic torque \( \sim (GM_{UT}/r^2) M_{UT} \sim GM_{UT} \rho_g r^2 \). The required gas density

\[
\rho_g \sim \frac{1}{t_{\text{slow}}} \sqrt{ \frac{\rho_{UT}}{G} } \approx 3 \times 10^3 \text{ g/cm}^3 \approx 10^{-11} \text{ g/cm}^3 \frac{3 \times 10^7 \gamma}{t_{\text{slow}}} \tag{15}
\]

where \( t_{\text{slow}} \) is the characteristic slowing time. This is not implausible in the proto-Solar System. A mass \( \sim 1 \text{ (10^7 yr/t_{slow}) M}_{\odot} \) of gas would fill an oblate spheroid of major radii \( a = 44 \text{ AU} \) and axial ratio comparable to the inclination of Ultima Thule to such a density.

7 DISCUSSION

The values of \( P_{\text{evap}} \) corresponding to recession rates \( v_{\text{min}} \) and \( v_{\text{max}} \) are indicated in Fig. 1. NH3, HCN and C2H4 all have vapor pressures that would permit deposition of high albedo frost in shaded regions of Ultima Thule but low enough that they would not be lost entirely during the age of the Solar System; CO2 is a marginal member of this class. Of these, only NH3 is expected to be abundant, and may be the dominant constituent of Kuiper Belt objects.

With a spin axis roughly in the orbital plane, some portions of the surface are in shadow for more than a century, or (in craters or depressions) permanently. The characteristic thermal relaxation time of Ultima Thule \( r^2 C_{p,s}/K \approx 10^{13} \text{ s} \). Surfaces permanently shadowed are warmed only by conduction through the interior from sunlit surfaces, and cool to \( T_{\text{min}} \approx (T_{\text{max}} K/\sigma S_B)^{1/4} \approx 25 \text{ K} \). This is low enough to
retain CO, CH₄ and N₂. However, these cannot be the areas showing high albedo, because albedo was measured when they were sunlit. Night-time surfaces have temperatures between $T_{\text{max}}$ and $T_{\text{min}}$.

The present shape of Ultima Thule can only be maintained by solids of strength $\gtrsim G\rho r^2 \sim 3 \times 10^4$ dyne/cm$^2$. This is very small, about 0.03 of Earth’s atmospheric pressure, but must have been maintained since the two lobes came into contact. Ices have strengths orders of magnitude greater and at the temperature of Ultima Thule are not expected to creep.

The fact that Ultima Thule consists of two roughly spherical lobes in contact, in contrast to apparently highly prolate 1I/2017 U1 ‘Oumuamua (Meech et al. 2017), implies a different origin and history. ‘Oumuamua may have acquired its shape and been expelled from its parent planetary system during a luminous post-main sequence phase of its star (Katz 2018). In contrast, Ultima Thule may have been formed by gas drag when the proto-Solar System was filled with comparatively dense gas out to the Kuiper Belt. Some fraction of its less volatile constituents condensed to form solid Kuiper Belt objects, while the uncondensable hydrogen and helium, much the greater part of its mass, exerted drag forces that removed angular momentum from proto-binary objects, shrinking their orbits and slowing their rotation after forcing binaries into contact. This hypothesis predicts that other Kuiper Belt objects may resemble Ultima Thule, rotating slower than their breakup rates, or be close binaries, and may be tested by their stellar occultations.

The sphericity of the lobes of Ultima Thule requires explanation. Whatever process spherized them must have ceased before they came into contact, because Ultima Thule itself was not spherized. The triple point of ammonia is 195.4 K, so it is implausible that the lobes were warm enough to have been liquid, and the triple point vapor pressure ($6 \times 10^4$ dyne/cm$^2$) would have led to their rapid evaporation. However, if $P_{\text{vap}} \gg P_{\text{max}}$ (the inequality resulting from the requirement that vapor transport was significant in much less than the present age of the Solar System) then transport in the vapor phase was significant. Not only (weak) gravity but also the higher temperatures of convexities and the lower temperatures of concavities would tend to round their shape. In the comparatively dense gas of the proto-Solar System evaporated molecules do not escape on ballistic trajectories but diffuse in a boundary layer and are readily recondensed. For this to be effective in $\sim 10^7$–$10^8$ y would require $T \approx 80$–90 K, consistent with a proto-Sun on its Hayashi track.

Accurate estimation of the surface temperature of any icy outer Solar System object requires measurement of the far-IR emissivity (equal to the absorptivity, directly measurable in the laboratory) of the ices it is likely to comprise.

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