A PRISTINE "CONTACT BINARY" IN THE KUIPER BELT: IMPLICATIONS FROM THE *NEW HORIZONS* ENCOUNTER WITH 2014 MU_{69} ("ULTIMA THULE").

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Introduction: Spectacular images and other data from the 1 January 2019 *New Horizons* encounter with the distant cold classical Kuiper belt object (CCKBO) 2014 MU_{69} (nicknamed Ultima Thule) have revealed a binary planetesimal, the product of a gentle, low-velocity merger during the Solar System's accretional epoch. The roughly spherical shapes of the individual lobes (referred to here as "Ultima" and "Thule") likely reflect the low-velocity accumulation of numerous even smaller planetesimals, though confirmation of this awaits receipt of higher-spatial-resolution, higher-phase panchromatic, color, and spectral images taken at closest approach and scheduled for downlink before this conference. Preservation of Ultima Thule's "contact binary" shape likely reflects the relatively benign dynamical and collisional environment of the cold classical Kuiper belt over time, providing the clearest window to date into the accretion processes operative in the protosolar nebula and subsequent planetesimal disk.

The Cold Classical Kuiper Belt: Following the 2015 Pluto system encounter [1], the *New Horizons* mission embarked on an extended exploration of the Kuiper belt [2], climaxing (for now) with the flyby of a small world only discovered through concentrated effort in 2014 (after nearly a decade of ground-based searches) by the *Hubble Space Telescope* [3]. With orbital elements $a = 44.2$ AU, $e = 0.03$, and $i = 2.4°$, 2014 MU_{69} is a denizen of the CCKB, a reservoir of mainly small bodies on non-resonant, low-eccentricity (e), low-inclination (typically $i < 5°$), i.e., *dynamically cold*, orbits, with heliocentric semimajor axes (a) between 40 and 48 AU [4]. The cold classicals have a size-frequency distribution, wide-binary fraction, and red colors distinct from the dynamically hot and resonant populations of the Kuiper belt, implying a distinct formation and/or dynamical history. The present consensus is that the cold classicals formed in-place and largely (but not necessarily entirely) escaped perturbations by giant planet migration, making them the most distant known remnants of the original protoplanetary disk [4]. The prospect of a close spacecraft encounter with one was eagerly anticipated [5].

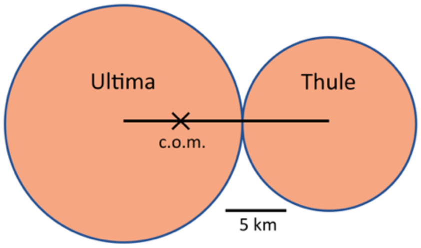

Figure 1. Idealized model of Ultima Thule as a contact binary of two spheres. For equal densities of both lobes the center-of-mass is shown and the mass ratio is 72/28.

What *New Horizons* Has Revealed So Far: The principal results of the encounter are summarized in [6]. Ultima Thule is revealed as not merely bi-lobed, but as two discrete, quasi-spherical lobes (mean radii in projection 9.73 and 7.12 km, respectively) joined at a narrow neck (Fig. 1). It is in this geometric, cojoined sense that we refer to Ultima Thule as a "contact binary." In projection "Ultima" is more distinctly ellipsoidal or topographically rugged than "Thule." The long axes of both bodies (again, in projection) neither align nor anti-align with the long axis of the binary as a whole [7]. The vis-nIR colors of both lobes are the same to present measurement accuracy and consistent with the red colors of CCKBOs [8].

The binary is a highly oblique rotator, spinning with a roughly 15-hr period and an obliquity close to 90° [9]. For equal bulk density (ρ) lobes, the center of mass is well within the body of Ultima (Fig. 1). The synchronous orbit period of two barely touching spheres of the above sizes is $9.0 \times (\rho/500 \text{ kg m}^{-3})^{-1/2}$ hr. Given that 500 kg m^{-3} is a likely lower limit density for small, highly porous, comet-like bodies [10], if MU_{69} formed as a collapsed binary pair [11], then a mechanism is necessary to further slow its spin. (But we also emphasize that the CCKBOs are *not* a source reservoir for today's comets [12].) Escape speed from the binary is $\approx 6 \text{ m/s} \times (\rho/500 \text{ kg m}^{-3})^{1/2}$, whereas the collision speed of Ultima and Thule from infinity (and $\upsilon_\infty = 0$) would have been $\approx 4.5 \text{ m/s} \times (\rho/500 \text{ kg m}^{-3})^{1/2}$.

Implications for Accretion: The foremost direct conclusion one derives from the available images is that Ultima and Thule must have collided/merged at a *very* low velocity. Numerical experiments of collisions of km-scale porous icy aggregates [13] indicate closing velocities no greater than their mutual escape speed (several m/s *or less*) and an oblique strike are necessary for discrete binary preservation (as opposed to fuller fusion & no preserved neck). The question then arises as to the origin of the quasi-spherical lobes themselves. A simple explanation is that Ultima and Thule formed from the ~isotropic accretion of myriad smaller bodies (boulders or "pebbles"). Alternatively, intermediate-scale planetesimals could have piecewise built Ultima and Thule, but if these accreted at ≈1-to-a-few m/s, they may have totally deformed upon impact, forming "splats" [13]. If so, evidence of accreted layers or other rolling topography may be forthcoming in high-resolution images [14].

In contrast, the shapes of Ultima and Thule have resisted slumping in to fill the neck region [15], which implies at least some measure of material strength. Rugged km-scale topography on Ultima's horizon [7] implies stresses of order $\rho g h/3$, or ≈200 Pa for ρ = 500 kg/m^3, g = 0.0014 m/s^2, and h = 1 km. The topographic slopes appear to be under the angle of repose, however, so such stresses can be supported frictionally. The neck region is a different story, and may require tensile strengths in excess of 1 kPa. Such tensile strengths are high for comet-like bodies [13] and may imply some mild sintering, possibly due to the impact/accretion process of the individual lobes or, if there is a delay between lobe accretion and binary formation (see below), mild ^{26}Al heating and mobilization of supervolatile ices such as N_2 and CO [16].

Implications for Binary Formation: Many mechanisms have been proposed for small-body binary formation. Some (such as YORP spin-up and fission) apply only in the inner Solar System. In the outer Solar System, binary systems may form via 3-body exchange capture [17]. For this to work implies heliocentric encounter velocities generally on the order of the Hill speed [18], which for Ultima would have been ≈ 2 cm/s! Moreover, the binary formed would be either prograde or retrograde, but not highly oblique, and there would be no preference for equal or subequal binary pairs (a characteristic of the CCKBOs).

A more promising formation mechanism posits a swarm of locally concentrated solids in the protoplanetary nebula (as in, but not limited to, the streaming instability [SI, 19]) collapsing under its own gravity. This mechanism has been modeled in some detail for larger (100-km class) KB binaries [18]. The mechanism is highly efficient, and yields binary pairs with a broad range of separations and eccentricities, depending on total swarm mass and angular momentum (L). Merger speeds are appropriately low. In principle, an MU_{69}-like body could form directly in a collapsing swarm of the appropriate mass and angular momentum. Notably, the binary size ratios produced [18] are an excellent match to that of Ultima Thule (≈0.75).

Highly inclined (to the mean L vector of the initial swarm) binary orbits are not common in [18], but they do occur (at the ~10% level). This may not be a serious issue for low-L and/or turbulent swarms [20].

Dynamical Hardening? A possibility explored, in the context of bilobate 67P/CG, is that mutually orbiting binaries may have angular momentum extracted, collapsing them into a contact binary [11]. In the CCKB, relevant, non-exclusive processes include:

Gas Drag. Not considered effective for the particle surface over-densities characteristic of SI, once gravitational instabilities begin [18], this should probably be reexamined [20].

Kozai-Lidov. Oscillation of high-inclination mutual circular orbits with low-inclination eccentric ones (conserving the L component perpendicular to the heliocentric orbit plane) is a possibility in general [21], but not for Ultima Thule, as the resulting contact binary should have a low(er) inclination (not ~90°).

Tides. Probably only effective for very tight low-mass binaries, this mechanism does not shed angular momentum, but redistributes it to slowly rotating individual lobes (or to a close moon in the system, not yet detected). In Ultima Thule's case, Ultima (e.g.) would need to be rotating very slowly or even "retrograde" at the moment of tidally-induced contact.

Collisions. Impacts can bind or unbind a binary over time, but is only effective (at the ~50% level) for very close binaries [11]. The heliocentric impactor flux in the CCKB is predicted to be relatively low, however [22], which could render this mechanism moot. Observations of MU_{69}'s cratering record, and much else, in images and other data to be downlinked should provide important further constraints on the fundamental processes of planetary accretion.

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