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On the Origin of the Remarkable Contact Binary (486958) 2014 MU_{69} ("Ultima Thule")

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Abstract

The 1 January 2019 *New Horizons* encounter with the distant cold classical Kuiper belt object (CCKBO) 2014 MU_{69} revealed a binary planetesimal, the product of a gentle, low-velocity merger during the Solar System's accretional epoch. The roughly lenticular shapes of the individual lobes likely reflect the low-velocity accumulation of numerous, even smaller planetesimals. Preservation of MU69'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.

1. Introduction

The principal results of the encounter are summarized in [1], though the shape model has been updated since then [2]. Ultima Thule is revealed as two discrete, quasi-spherical lobes. The larger ("Ultima") is more lenticular (≈21 x 20 x 9.5 km), and is joined at a narrow neck to the somewhat smaller "Thule" (≈15.5 x 14 x 10 km). The principal axes of both bodies have now been determined to be remarkably aligned (all together, to within 5°; see image in [3], an alignment that is extremely unlikely to be due to chance). This is quite different than the impression at encounter time of two merged spheres (the "snowman"). In the latter case the two lobes could have merged from any direction, but the alignment of the principal axes, along with the geological evidence for a gentle as opposed to a catastrophic merger, strongly implies that the two lobes were once distinct bodies that orbited each other. The geometry is consistent with tidal alignment into a lowest energy, 1:1 spin-orbit configuration, driven by some combination of tidal dissipation, gas drag, or even grazing, "long-axis" collisions while one or both bodies were rotating faster than synchronously. In addition, the vis-nIR colors and spectra of both lobes are the same to measurement accuracy and consistent with the red colors of CCKBOs, in particular, ultrared objects such as Pholus [1]. The similarity of both lobes points to initial accretion from a compositionally uniform region of the CCKB.

The binary is a highly oblique rotator, spinning with a 15.9-hr period and an obliquity of 99° [2]. This is the synchronous orbit period for two barely touching, equal density (ρ) lobes if ρ = 290 kg m^{-3} [3]. This assumes the gravitational attraction between spheres; treating the shapes more explicitly (e.g., as ellipsoids) modestly increases the gravitational attraction and lowers this limiting density. Considering the range in plausible tensile and compressive strengths for a porous, comet-like bodies broadens the permissible density range as well. For example, greater densities would imply that the neck is in compression, but even assuming a "strong" comet cohesion of 10 kPa [4], the density must remain under 1000 kg m^{-3} lest the neck region collapse.

Ultima Thule must obviously possess some strength, otherwise it would collapse into a sphere. The gravitational slopes [3], however, are generally under the angle of repose for granular material, so the shapes of Ultima and Thule by and large can be maintained by frictional strength. But at regions near the neck, gravitational slopes exceed 35-40°, so these over-steepened surfaces must be held together by finite cohesion (of order a few 100 Pa). We note that the steepest gravitational slopes are found on one of Thule's "shoulders," coincident with a prominent trough, possibly a sign of incipient slope failure.

2. Accretion of a contact binary

A direct conclusion one derives from the New Horizons images is that Ultima and Thule must have collided/merged at a relatively low velocity. Escape speed from MU69 depends on density but is of the order of a few m/s. In contrast, even in the CCKB, with its low-*e*, low-*i* orbits, the median impact speed is 100 times higher. Heliocentric impacts between bodies similar to Ultima and Thule would have been catastrophic. We (DCR and JM) have undertaken a series of numerical experiments bodies of the appropriate scale, density, and strength, using the soft-sphere, pkdgrav N-body code [5]. The results are quite striking (Fig. 1). Oblique impacts at 10 m/s do not result in mergers, but in shearing or planing off sections of one or both bodies; even oblique impacts at 5 m/s lead to too much distortion and merging to be easily compatible with MU69's shape (e.g., no discrete neck). Only at even lower collision velocities do the numerical models resemble MU69. These results are clearly compatible with the dynamic environment implied by the geometric alignment above. But what leads to this environment?

3. The bigger picture

A very promising formation mechanism for binaries in the CCKB posits a swarm of locally concentrated solids in the protoplanetary nebula (as in, but necessarily not limited to, the streaming instability) collapsing under its own gravity. This mechanism has been modeled in some detail for larger (100-km class) KB binaries [6]. 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. MU69 may have been expelled from such a collapsing "pebble cloud," or may formed more directly in a low-mass version. Recent work has followed the gravitational concentration of mass in a 3D, numerical streaming instability simulation, one designed to determine/ match the initial mass function of the Kuiper belt [7]. Because of turbulence the angular momenta of the bound mass clumps span a range. The ratio of prograde to retrograde rotators is ~4:1, and the angular distribution is an excellent match to the observed orbital obliquities of CCKB binaries [7]. Thus MU69's high obliquity is not necessarily unusual. The final part of the puzzle is the dynamical "hardening" of the co-orbiting binary, but there appear to be several viable pathways [8].

Acknowledgements

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References

[1] Stern, S.A., et al. and 200+ coauthors: Initial results from the New Horizons exploration of 2014 MU_{69}, a small Kuiper Belt Object, *Science 364*, doi:10.1126/ science.aaw9771.

[2] Porter, S.B., et al.: The Shape and Pole of (486958) 2014 MU_{69}. DPS/EPSC (this conference), 2019.

[3] Keane, J.T., et al.: The Geophysical Environment of (486958) 2014 MU_{69}. DPS/EPSC (this conference), 2019.

[4] Jutzi, M., and Asphaug, E.: Formation of bi-lobed shapes by sub-catastrophic collisions, A late origin of comet 67P's structure, *Nature 348*, 1355–1358, 2015.

[5] Schwartz, S.R., Richardson, D.C., and Michel, P.: An implementation of the soft-sphere discrete element method in a high-performance parallel gravity tree-code, *Granular Matter 14*, 363-380, 2012.

[6] Nesvorný, D., et al.: Formation of Kuiper belt binaries by gravitational collapse, *Astronomical J. 140,* 785, 2010.

[7] Nesvorný, D., et al.: Trans-neptunian binaries provide evidence for planetesimal formation by the streaming instability, *Nature Astronomy,* in press, 2019.

[8] McKinnon, W.B., et al.: A pristine "contact binary" in the Kuiper belt: Implications from the *New Horizons* encounter with 2014 MU_{69} ("Ultima Thule"), LPSC abs. #2767, 2019.

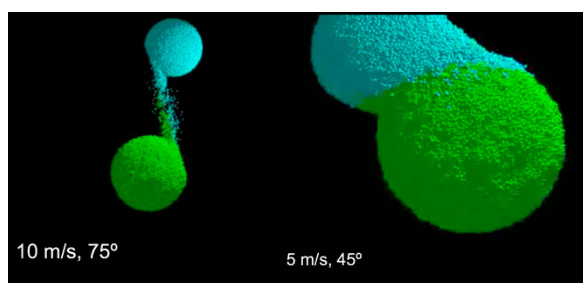

Fig. 1. Numerical simulation of collisions of Ultima and Thule, modeled as spheres.