ULTIMA THULE: POSSIBLE GRAVITATIONAL COLLAPSE SCENARIOS FOR ITS ORIGIN.

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Introduction: A theoretical understanding of how protoplanetary disks (pp-disks) produce planetesimals, i.e., the ~100 km sized building blocks of planets, remains a conundrum for the theory of planet formation. NASA's recent mission passed the informally named Ultima Thule (UT), a cold classical Kuiper Belt (CCKB) object with semi-major axis of 44.5 AU, may offer clues to this age-old question. Based on observations and theoretical considerations, we propose that there are at least 3 gravitational collapse settings worth exploring to explain the origins of such objects.

Observations of UT: NASA's New Horizons spacecraft imaging of 2014 MU$_{69}$ on January 1, 2019 [1] revealed a 15-hr rotating bi-lobed object whose constituents, informally referred to as Ultima (U) and Thule (T), appear nearly spherical with ~9.5 km and ~7.1 km radii (respectively) [2]. U and T have similar colors [3] with measured albedos ~ 0.1 [4], indicating that UT is a typical member of the CCKB class of objects [5]. Image analysis also indicates an absence of moons or other discernable debris [6]. On the assumption that U and T are indeed slowly rotating, contacting, nearly spherical bodies, and shape analysis suggest that UT's obliquity is nearly 92^{o} [7].

Observational/theoretical considerations: Analysis of non-carbonaceous chondrites show that they are composed of 1mm sized individual chondrules or their 1cm sized aggregates [8]. Collapse of solids in the outer solar system likely involved similarly scaled particle aggregates. Planetesimal forming regions of protoplanetary disks likely support turbulence driven by recently identified linear instability mechanisms, driving turbulence levels ~ $10^{-5}<\alpha<10^{-3}$ [9], which are likely operative in the outer solar system [10]. Evolutionary models of the Solar System's orbital architecture suggest that the CCKB region was not disrupted during the gas-giant planet migration phase, suggesting that CCKB bodies are likely bona fide remnants of the planetesimal formation era [11]. Turbulent pp-disk evolution models constrain particle growth-via-sticking [12]. All such models predict the evolution of a particle's Stokes number, $\mathrm{St} = \Omega(\rho_*/\rho_g)(a/c_s)$, which measures a particle's stopping time (based on Epstein drag) in terms of the local disk orbital frequency (Ω): a is particle radius, c_s is the local gas sound speed, and ρ_*, ρ_g are respectively the particle and gas mass densities. Particle growth in these evolution models, starting with μm sized grains, encounters several growth barriers (e.g., radial drift and fragmentation) limiting growth to $\mathrm{St} \leq \sim 0.01$ in the outer disk (>20 AU, ↔ mm to cm particle radii) [13]. *For these conditions particles are strongly affected by gas drag*. These models predict uniformly mixed particles – i.e., the mean particle to gas mass density ratios are equal to the corresponding local surface mass density ratios: $\rho_p/\rho_g \approx \Sigma_p/\Sigma_g \approx 0.01$.

Constraints on any formation scenario: Any formation hypothesis/scenario should treat how: (i) to produce a relatively slow orbiting contact binary, (ii) such pairs have the same color, and (iii) this formation process clears away all remaining local debris [14].

Three working gravitational collapse hypotheses. These observations of UT as well as the other known properties of binary CCKB objects suggests that these bodies were formed in close proximity to one another. Previous theoretical modeling suggests that growth of grains into planetesimals must somehow leap directly from mm/cm-sized grains all the way up to 20-100 km sized planetesimals [15]. All collapse processes probably involve gravitational instability (GI) as the final gateway to formation. We consider/review 3 possible scenarios that could explain the origins of UT:

1. Streaming instability induced GI. Particles orbiting in a gaseous pp-disk will experience a headwind since the disk gas has some pressure support causing it to orbit a little slower than the particles. This headwind causes the particle to drift radially inwards. Perturbations in this drift result in a momentum exchanging resonance between gas and particles called the Streaming Instability (SI) [16,17]. The SI can drive strong overdensities in the local particle density, ρ_d which, in turn, can trigger GI [18]. The SI operates most effectively for (i) low turbulence, i.e., $\alpha<3\mathrm{x}10^{-6}$ [19], (ii) for $0.1<\rho_p/\rho_g<3$, and (iii) for $0.1<\mathrm{St}<3$, for which collapse occurs on local heliocentric rotation times. [20,21] demonstrates this process readily occurs for disk models $(\Sigma_p/\Sigma_g) \approx 0.1$ and $\mathrm{St} = 0.006$. Such conditions result in particle settling toward the disk-

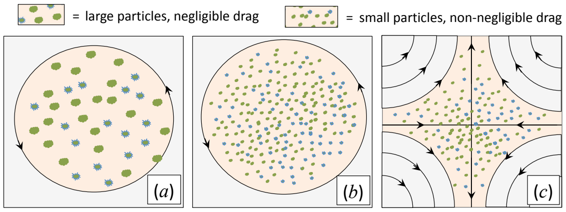

Figure 1. The 3 collapse settings proposed in text: (a) laminar swirl with large particles, (b) laminar swirl with small particles (gas drag non-negligible), (c) high strain/shear zone & small particles (for TC).

midplane resulting in over-densities sufficient to trigger SI -- all occurring over several dozen orbit timescales. ***However, these conditions are possible only in very weakly turbulent disks*** ($\alpha<10^{-6}$). Owing to the inability to directly resolve GI for dust particles in full 3D pp-disk simulations, [22] take the results of SI simulations [e.g., 21] as a starting point to follow the fate of collapsing swirling particles whose sense of spin aligns with the disk normal direction [23]. They start with a laminarly swirling, relatively high density of St ~ 0.1 particles and follow their gravitational collapse: *aerodynamic drag is thought to be a secondary effect*. Such an initial collapse scenario, i.e. a swirling collection of particles gravitationally collapsing with negligible aerodynamic drag, is depicted in Fig. 1a.

2. Nearly-laminar vortex induced GI. [24] demonstrate that disk anticyclones (i.e., vortices whose rotation vectors, as viewed from the local disk rotation frame, are opposite to that of the global rotation vector) trap particles since such whirls are pressure extrema. 3D simulations of the Vertical Shear Instability, one of the aforementioned mechanisms driving turbulence in cold pp-disks [9], show the emergence of such relatively long-lived laminar disk anticyclones drifting in an otherwise turbulent flow [25]. These vortices can be sites into which St = 0.01 particles may be swept up, albeit after several dozens of orbit times. Recently [26] demonstrate that 3D simulations of dust accumulating vortices do not result in the destruction of the vortical structure. Provided the vortex intrinsically survives long enough to trap the requisite overdensity of particles, then GI emerges: a nearly steady swirl of particles undergoing collapse under the influence of aerodynamic drag (Fig 1b).

3. Turbulent concentration (TC) induced GI. Borrowing from terrestrial cloud formation studies, [27] proposed that particle concentrations in turbulent flows, which are highly variable in space, scale and time, can lead to regions with overdensities large enough to sediment into a "sandpile" planetesimal. In TC eddies "centrifuge out" particles whose *turbulent* Stokes numbers (St_t , like St but where Ω is replaced by the local eddy frequency) are nearly 1, and particles cluster in regions of low vorticity and high strain rate. For values of St = 0.01 and a range of $10^{-4}<\alpha<10^{-3}$, [28-30] statistically assess the probability of turbulently triggering GI per unit time and show that they compare favorably against reasonable estimates based on the known CCKB population. For the CCKB, they find that cm sized particles under pp-disk conditions -- and requiring only modest enhancements in Σ_p/Σ_g (= 0.03) – can, via GI, leapfrog *with reasonable probability* into 10-20 km sized bodies. Based on the St and α input parameters, the length scales on which this could occur in the Kuiper Belt is ~10^4 km [26], which is about a factor of 10 less than UT's estimated Hill sphere.

Unlike the previous two scenarios, TC has no preferred initial swirl orientation. To date, there is no detailed examination of how such a configuration collapses under these conditions. This gives rise to our third proposed collapse scenario: an overdense collection of swirling particles collapsing under the influence of aerodynamic drag in an imposed steady flow field characterized by both strain and shear (Fig 1c).

Results: We will present simulation results following the gravitational collapse of overdense St = 0.01 particles under the influence of aerodynamic drag in both a laminar vortex model as well as in a flow field characterized by strain and shear (Figs. 1b/c).

References: [1] Stern et al. (2019) *LPSC L.* [2] Moore J.M. et al. (2019) *LPSC L.* [3] Grundy W. et al. (2019) *LPSC L.* [4] Hofgartner J. et al. (2019) *LPSC L.* [5] Benecchi S.D. et al. (2009) *Icarus, 200*, 292. [6] Spencer J. et al. (2019) *LPSC L.* [7] Porter S. et al. (2019) *LPSC L.* [8] Simon S.I. et al. (2018) *EPSL, 494* 69. [9] Lyra W. and Umurhan O.M. (2019) PASP – to appear (arXiv:1808.08681). [10] Malygin M.G. et al. (2017) *A&A, 605*, A.30. [11] Tsiganis K. et al. (2005) *Nature, 435*, 459. [12] Birnstiel T. et al. (2016) *SSR, 205*, 41. [13] Estrada P.R. et al. (2016) *ApJ, 818*, 200. [14] McKinnon et al. (2019) *LPSC L.* [15] Johansen A. et al. (2015) Asteroids IV, 471 (arXiv:1505.02941). [16] Youdin A. N. and Goodman J. (2005) *Apj, 620*, 459. [17] Squire J. and Hopkins P.F. (2018) *MNRAS, 477*, 5011. [18] Johansen A. et al. (2007) Nature, 448, 1022. [19] Umurhan O.M. et al. (2019) *ApJ* – in prep. [20] Carrera D. et al. (2015) *A&A, 579*, A43. [21] Simon J.B. et al. (2017) *ApJL, 847*, L12. [22] Nesvorny D. et al. (2018) *AJ, 155*, 246. [23] Nesvorny D. et al. (2010) *AJ, 140*, 785. [24] Barge P. and Sommeria J. (1995) *A&A, 295*, L1. [25] Manger N. and Klahr H. (2018) *MNRAS, 480*, 2125. [26] Lyra W. et al. (2018) *RNAAS, 2*, 195. [27] Cuzzi J.N. et al. (2010) *Icarus, 208*, 518. [28] Hartlep T. et al. (2017) *PRE, 95*, 033115. [29] Hartlep T. and Cuzzi J.N. (2017) *Accretion: Building New Worlds Conf.* [30] Hartlep, T. et al. (2019) *LPSC L.*