The solar nebula origin of (486958) Arrokoth, a primordial contact binary in the Kuiper belt

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Outline

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2. Arrokoth and Its Characteristics
3. Merger Speed Constraint
4. Binary Formation
5. Merger Mechanisms
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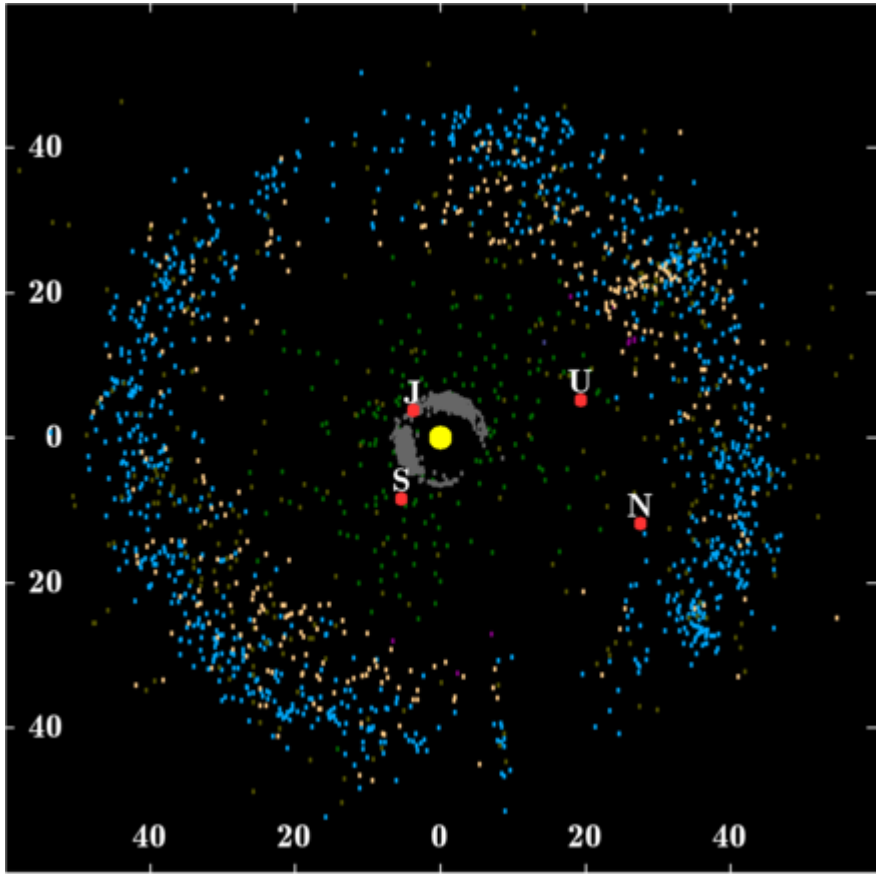
Kuiper Belt

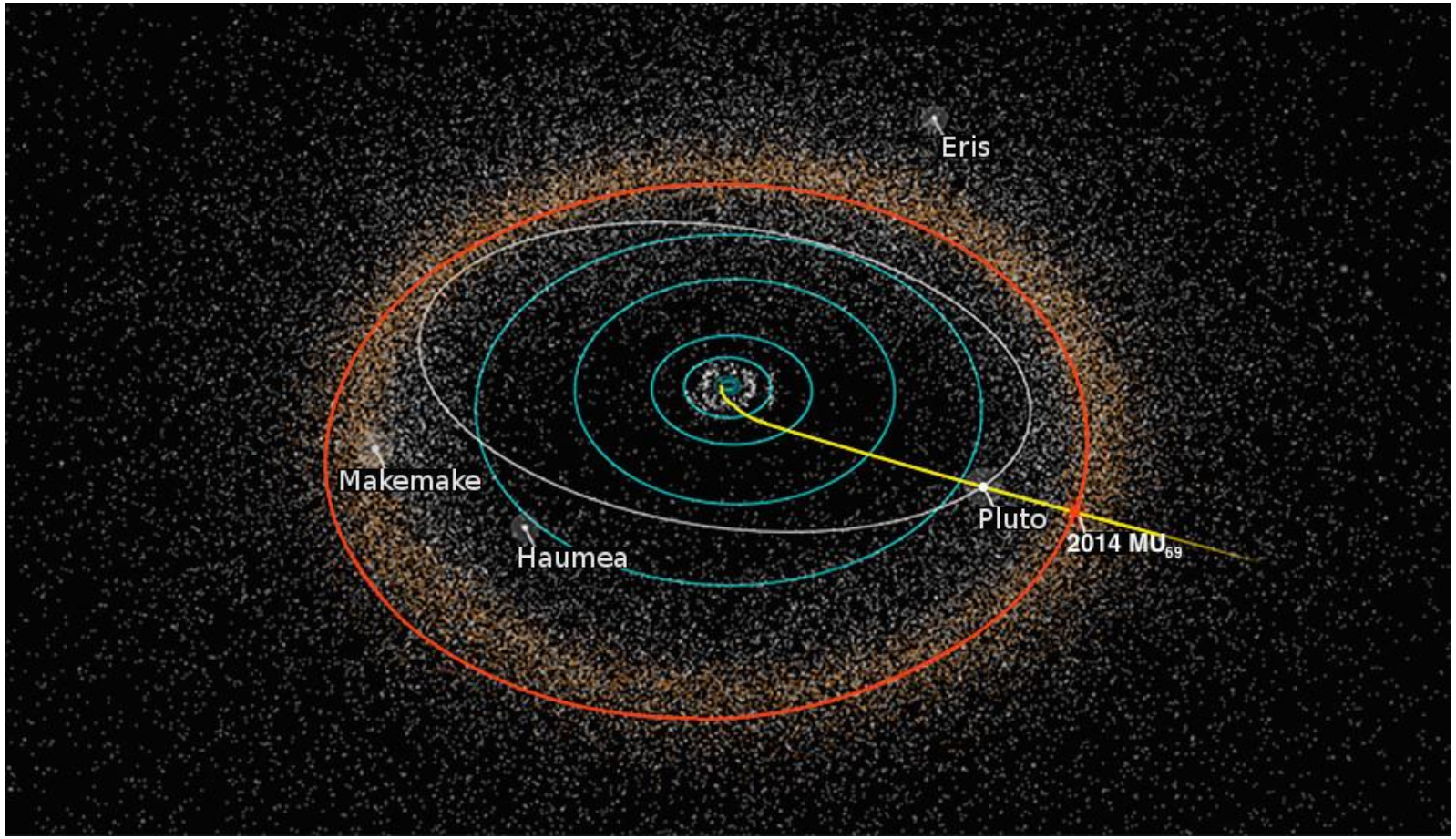


- Kuiper belt is a circumstellar disc in the outer Solar System.
- It extends from the orbit of Neptune at 30 AU to approximately 50 AU from the Sun.
- The cold classical Kuiper belt (CCKB) is a part of the non-resonant classical Kuiper belt located farther(>40AU)

New Horizons Spacecraft

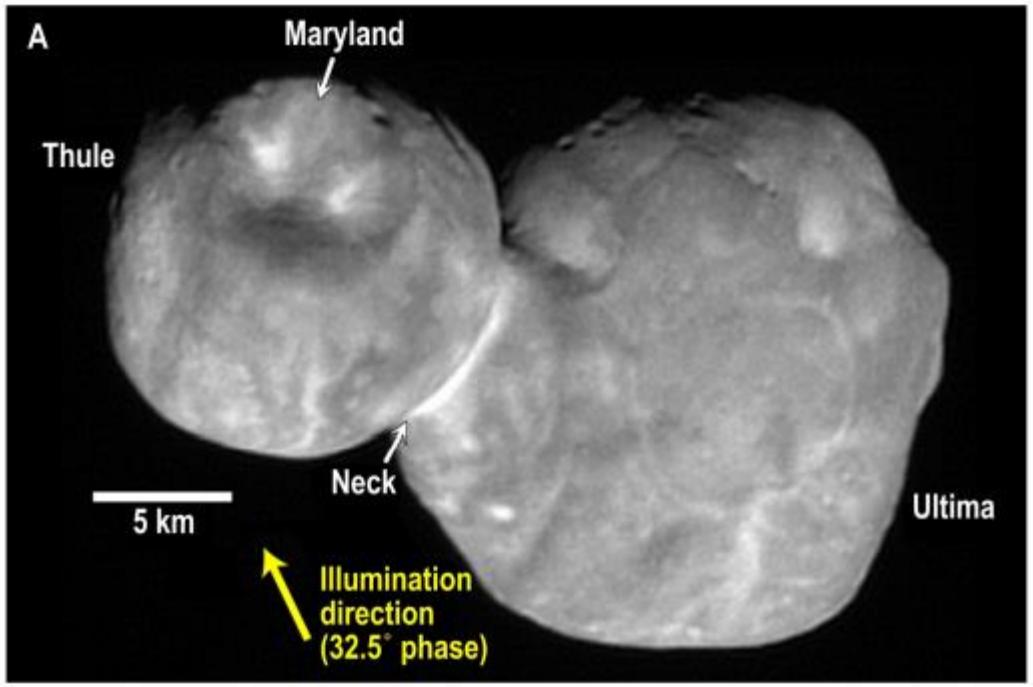
- New Horizons is the first mission to the Pluto system and the Kuiper belt
- New Horizons was launched on Jan. 19, 2006. It swung past Jupiter for a gravity boost in 2007.
- It conducted a six-month-long flyby study of Pluto and its moons in summer 2015

The Journey to the Kuiper belt



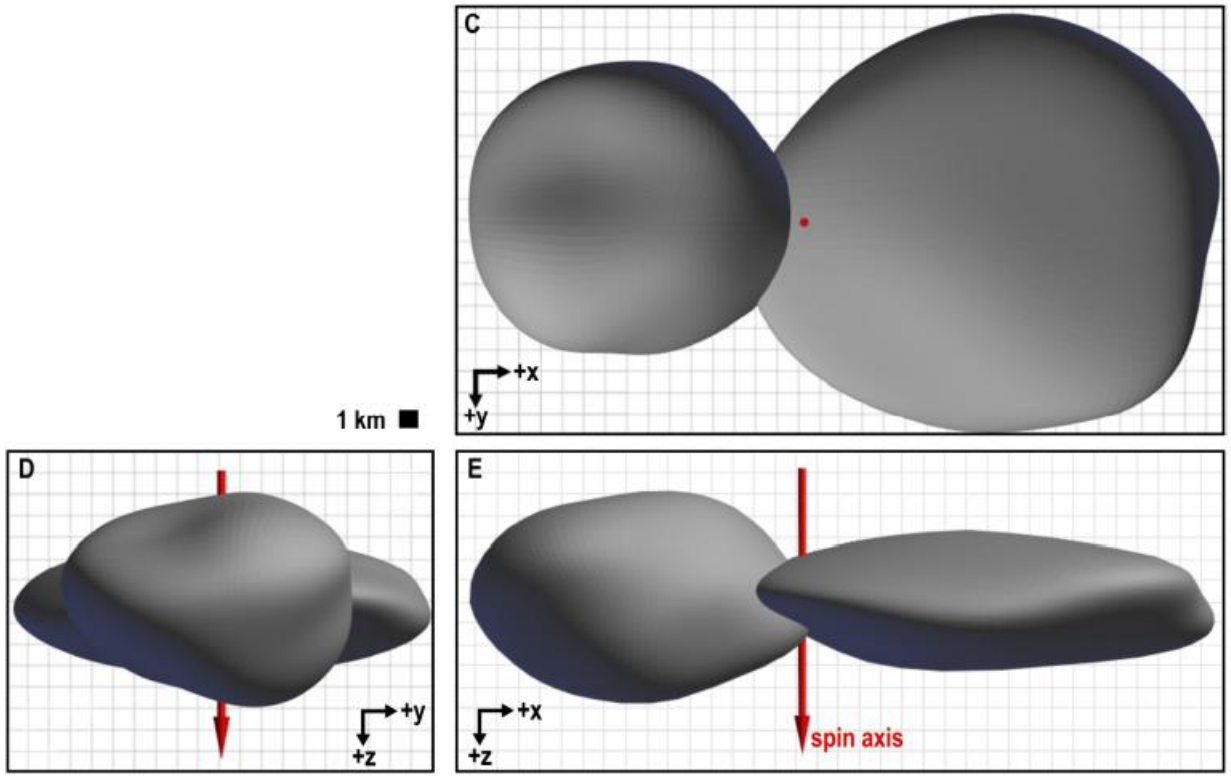
the spacecraft is expected to head farther into the Kuiper Belt

Arrokoth: Basic Info



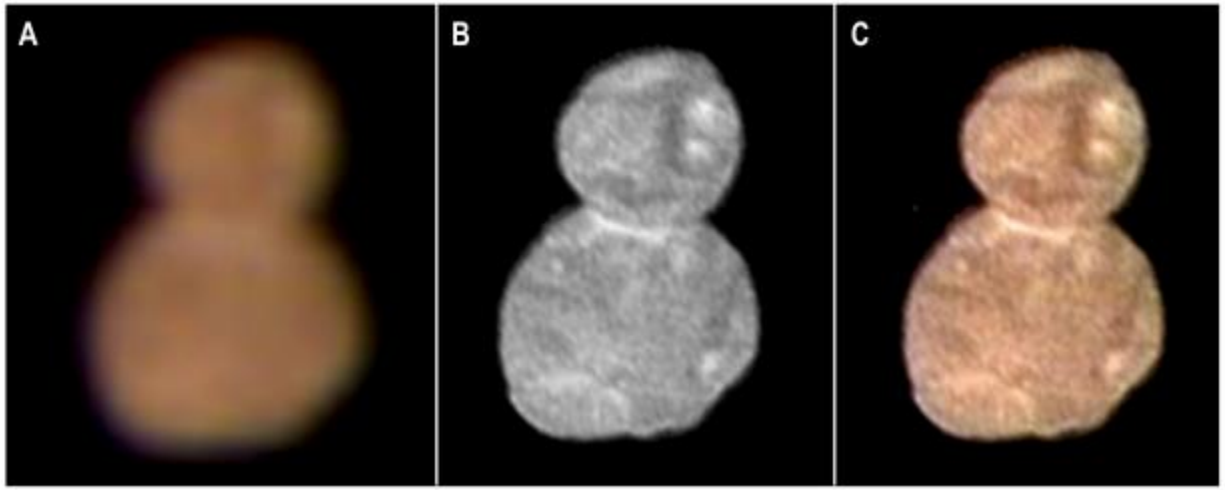
- Arrokoth is a contact binary in the CCKB, also known as “Ultima Thule”(天涯海角).
- The most distant object ever visited by human’s spacecraft
- Semimajor axis = 44.2 AU
- Eccentricity = 0.037
- Inclination = 2.54°

Arrokoth: Shape and Alignment

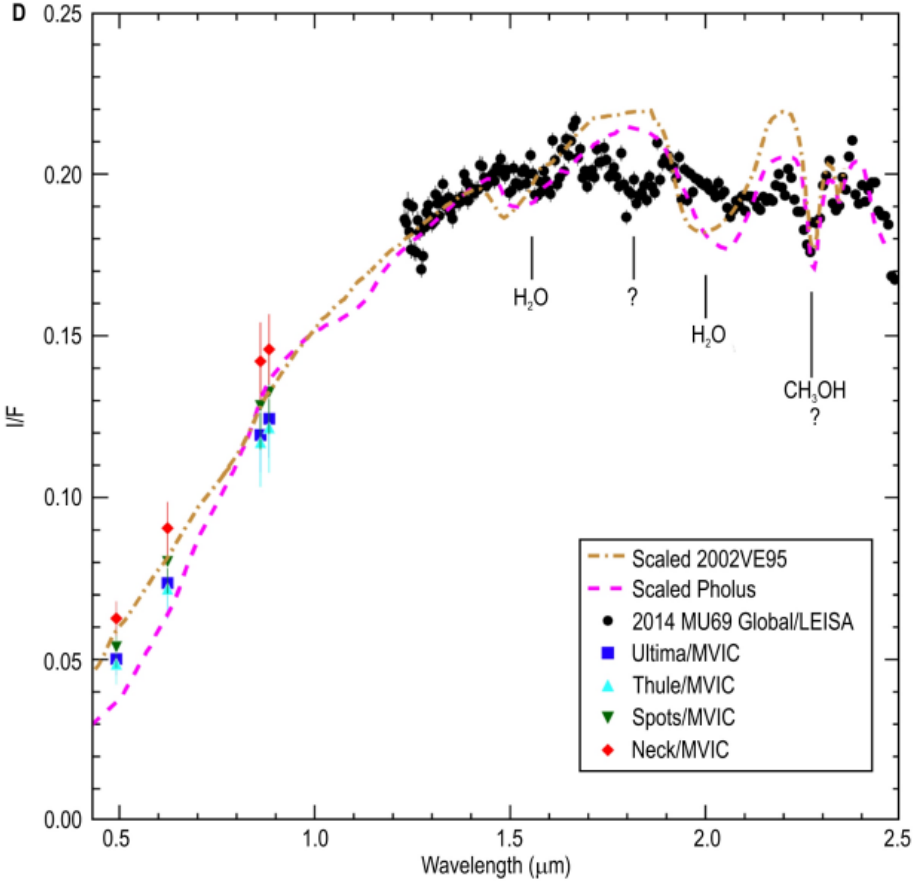


- bi-lobed system, consists of two ellipsoidal lobes jointed at a narrow “neck”
- diameter: 15.9km(larger lobe), 12.9km(smaller lobe)
- larger lobe is more oblate
- spin period: 15.9 hours
- spin obliquity: 99°
- both minor axes are aligned to the spin axis

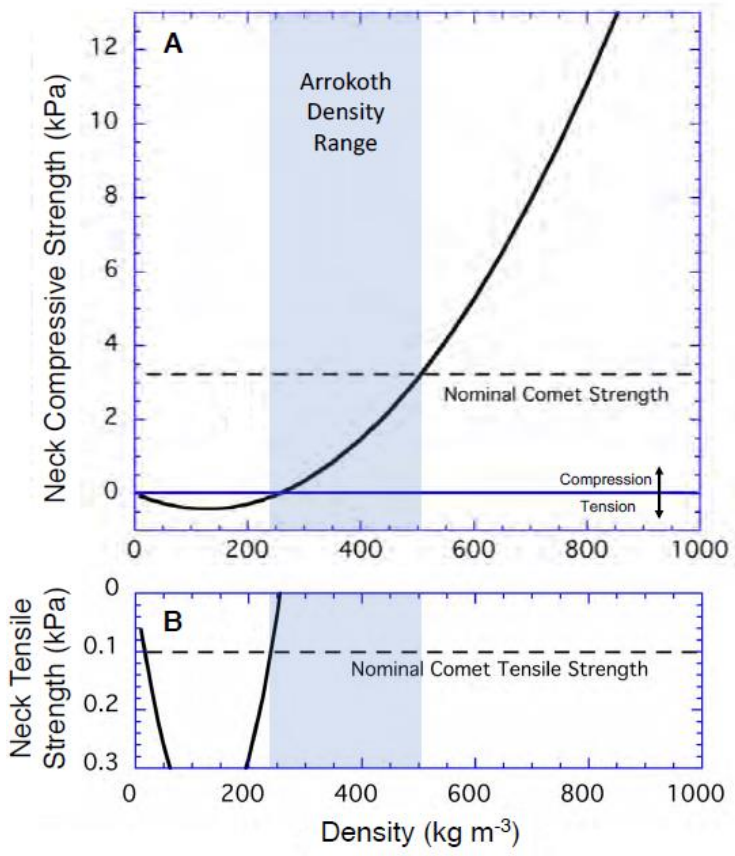
Arrokoth: Spectral Absorptions



- two lobes have the same color.
- presence of icy water & methanol



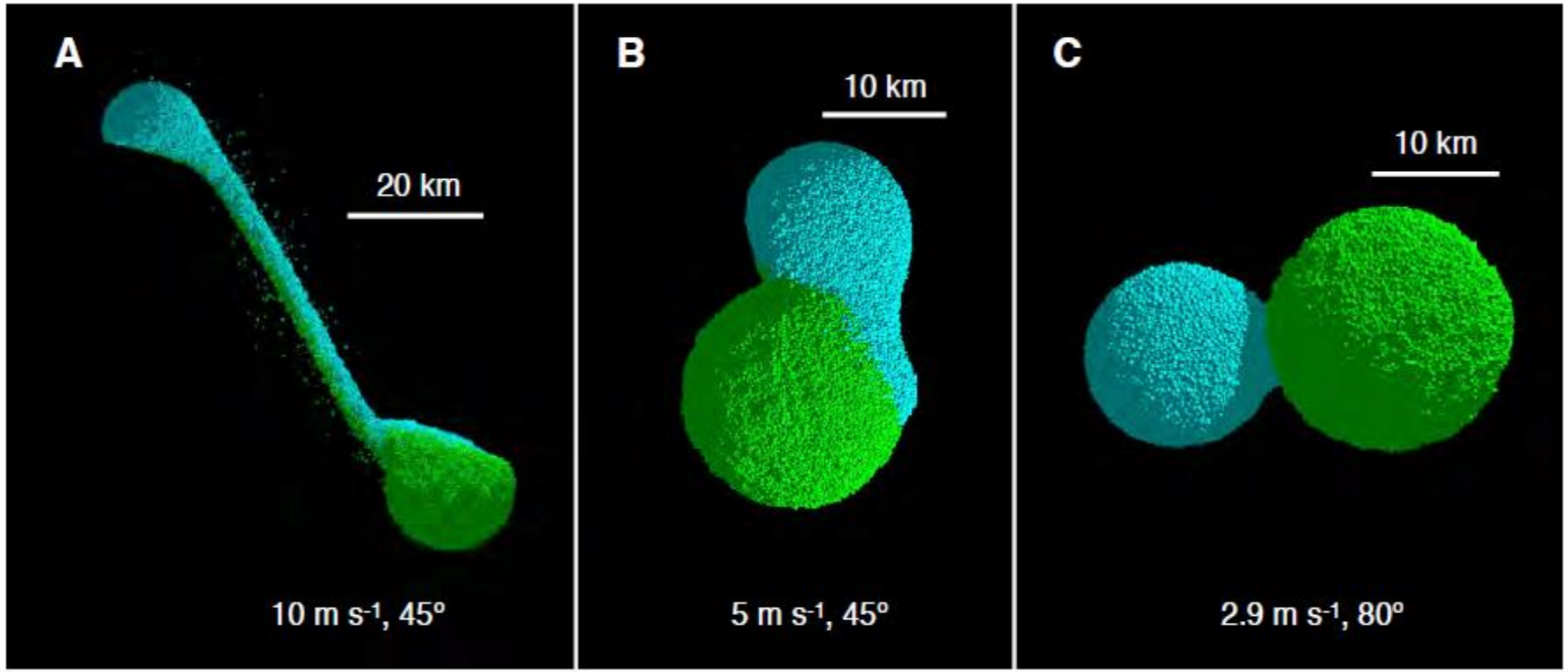
Arrokoth: Density Estimation



- Bulk density range: (250kg/m³, 500kg/m³).

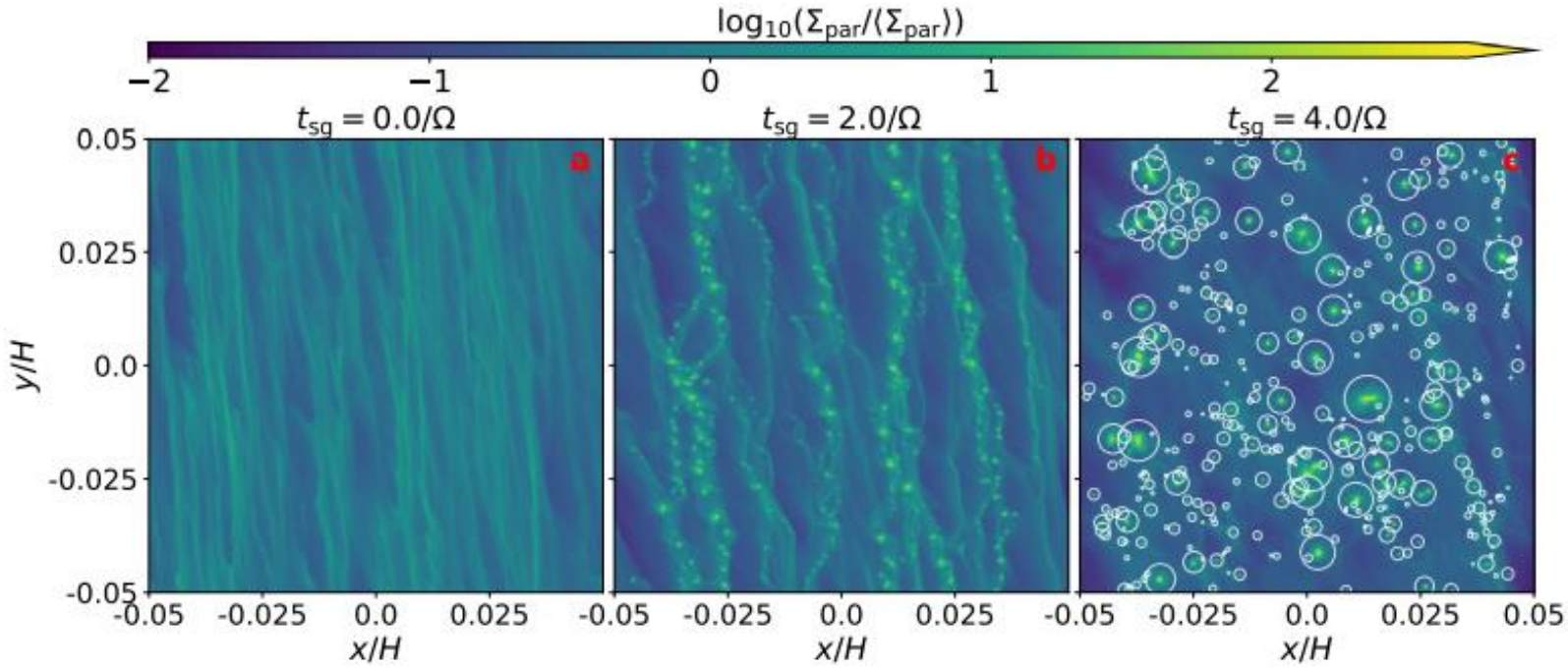
solid blue line : separates the compression and tension regimes
dashed line : limit compressive strength of cometary bodies
density > 250kg/m³ : neck is in compression
density > 500kg/m³ : neck would collapse

Merger Speed Constraints



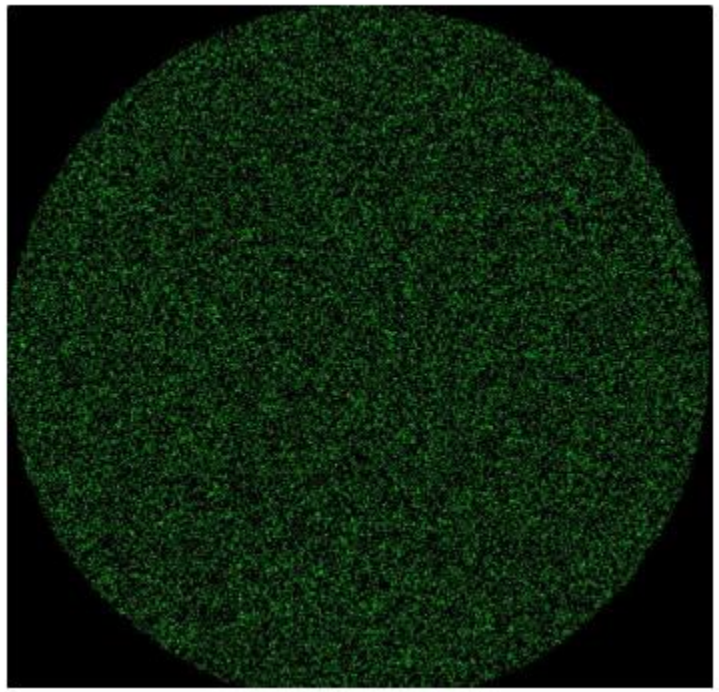
- The merger speed is likely sufficiently slow that the two bodies have already been gravitationally bound to each other prior to the collision

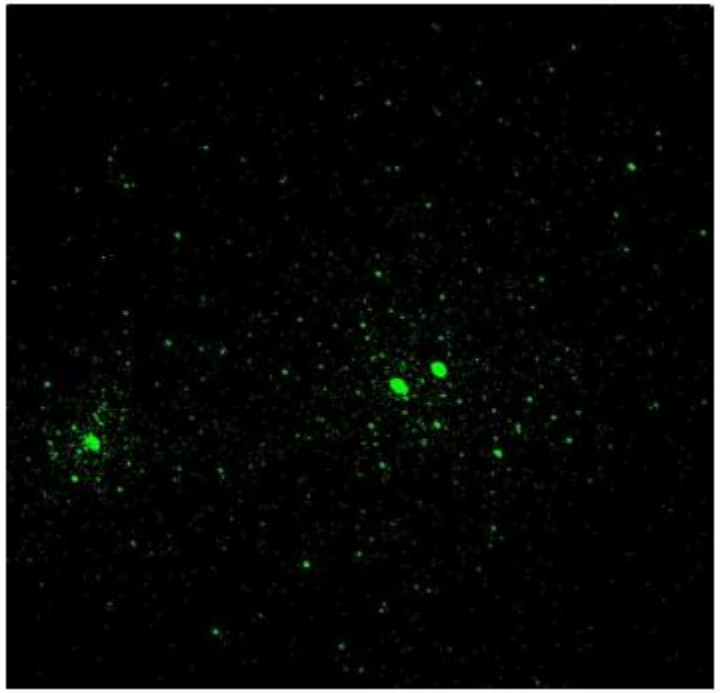
Binary Formation: Streaming Instability(SI) Clumps



swarms of solids → streaming instability → filaments, clumps

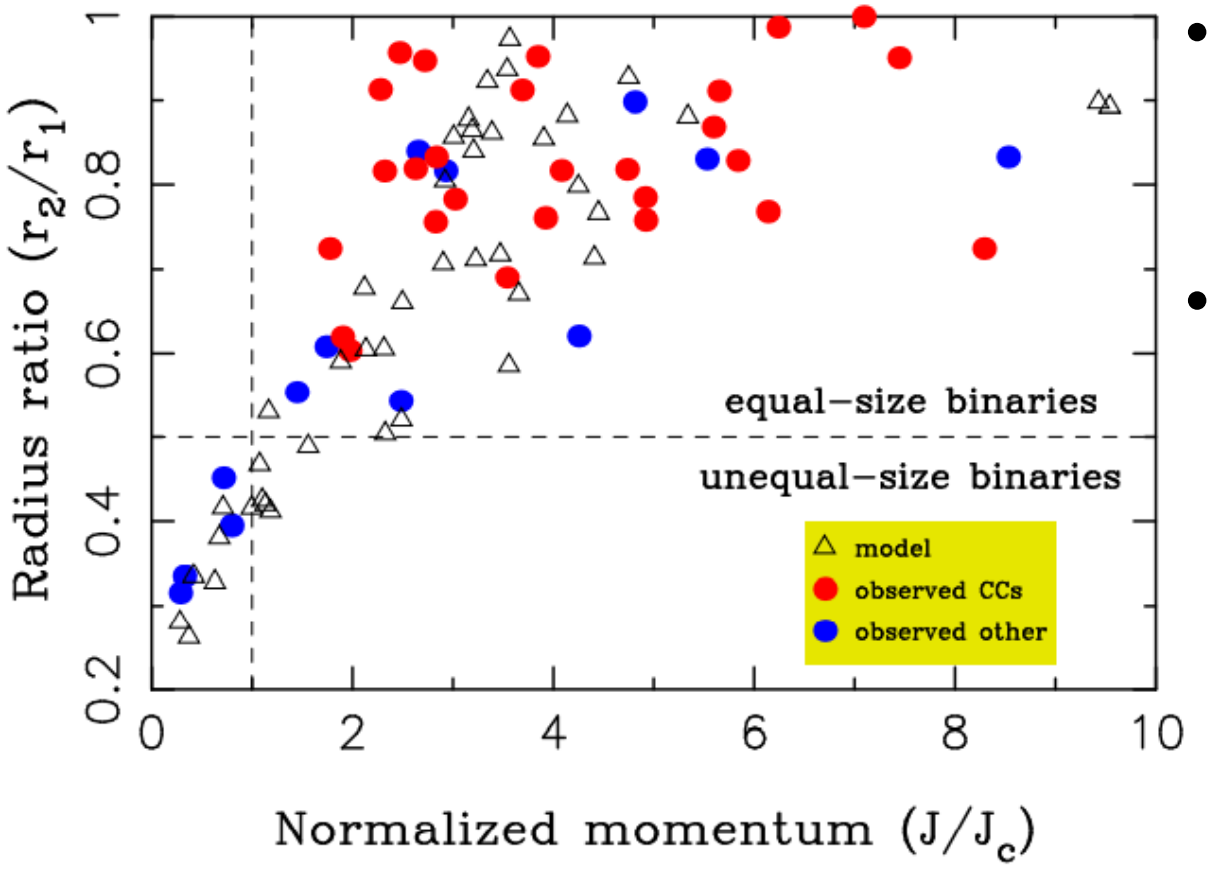
Binary Formation: Gravitational Collapse





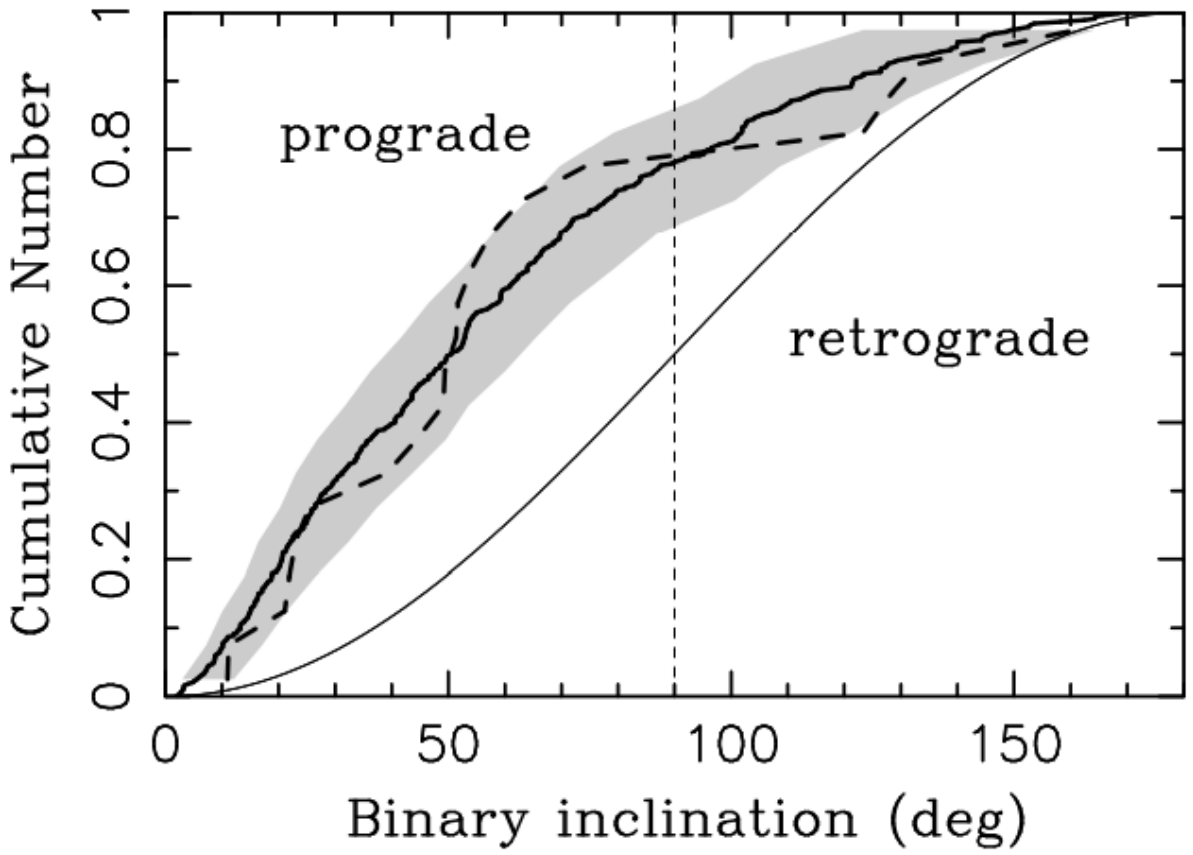
swarms of solids → (streaming instability) filaments, clumps → (gravitational collapse; initial angular momentum) co-orbiting binaries

Angular Momentum of Clumps



- J_c is the angular momentum of critical rotating Jacobi ellipsoid
- If $J > J_c$, the typical SI clump cannot collapse into an isolated planetesimal

Spin Orientations of Clumps



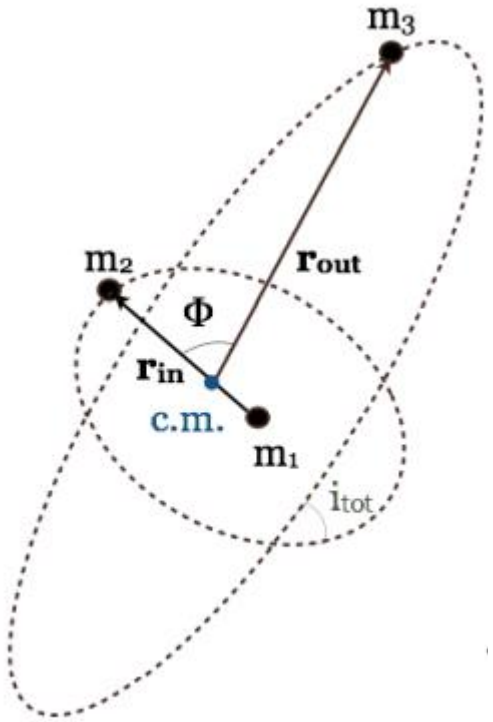
- The prograde binaries is dominant in the CCKBOs
- The binary inclinations from SI model are also consistent with the observation. Nearly 80% binaries are prograde systems

prograde orbit: inclination < 90°
retrograde orbit: inclination > 90°

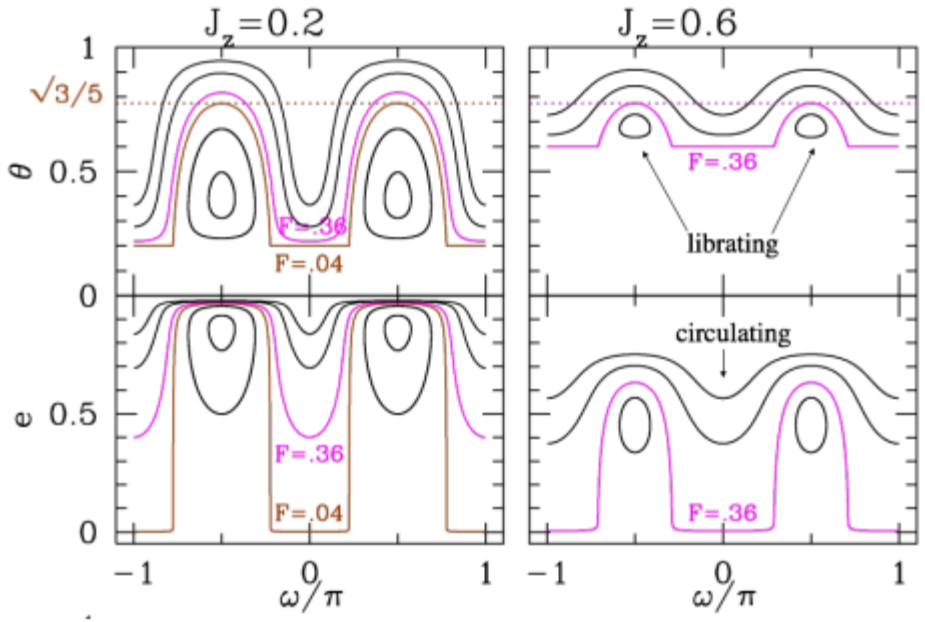
dashed bold line: the observation of trans-Neptunian binaries

solid bold line: the SI model results

Merger Mechanisms: Kuzai-Lidov Effect



$\theta = \cos i_{tot}$



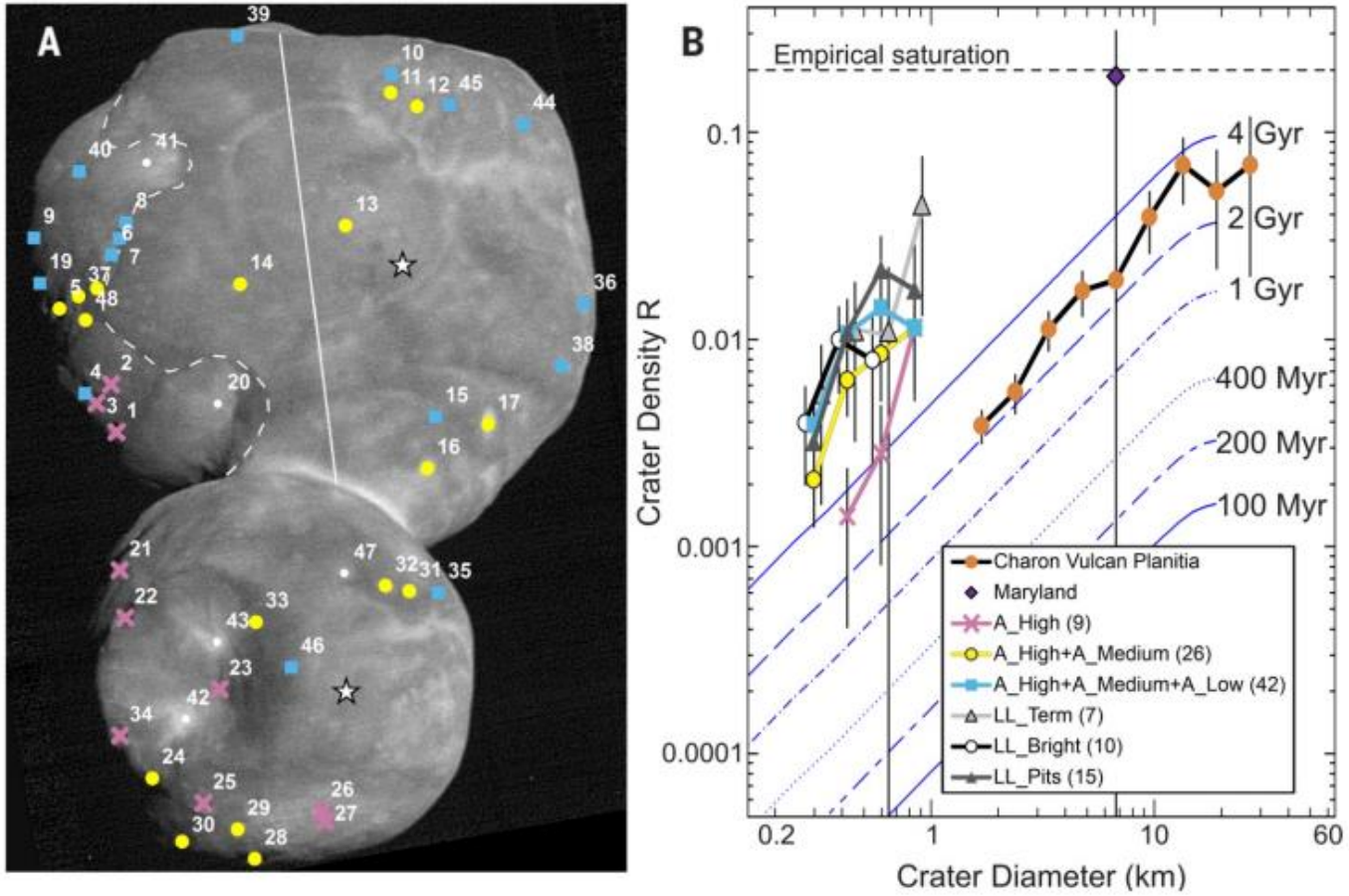
high eccentricity , low inclination

↓

low eccentricity , high inclination

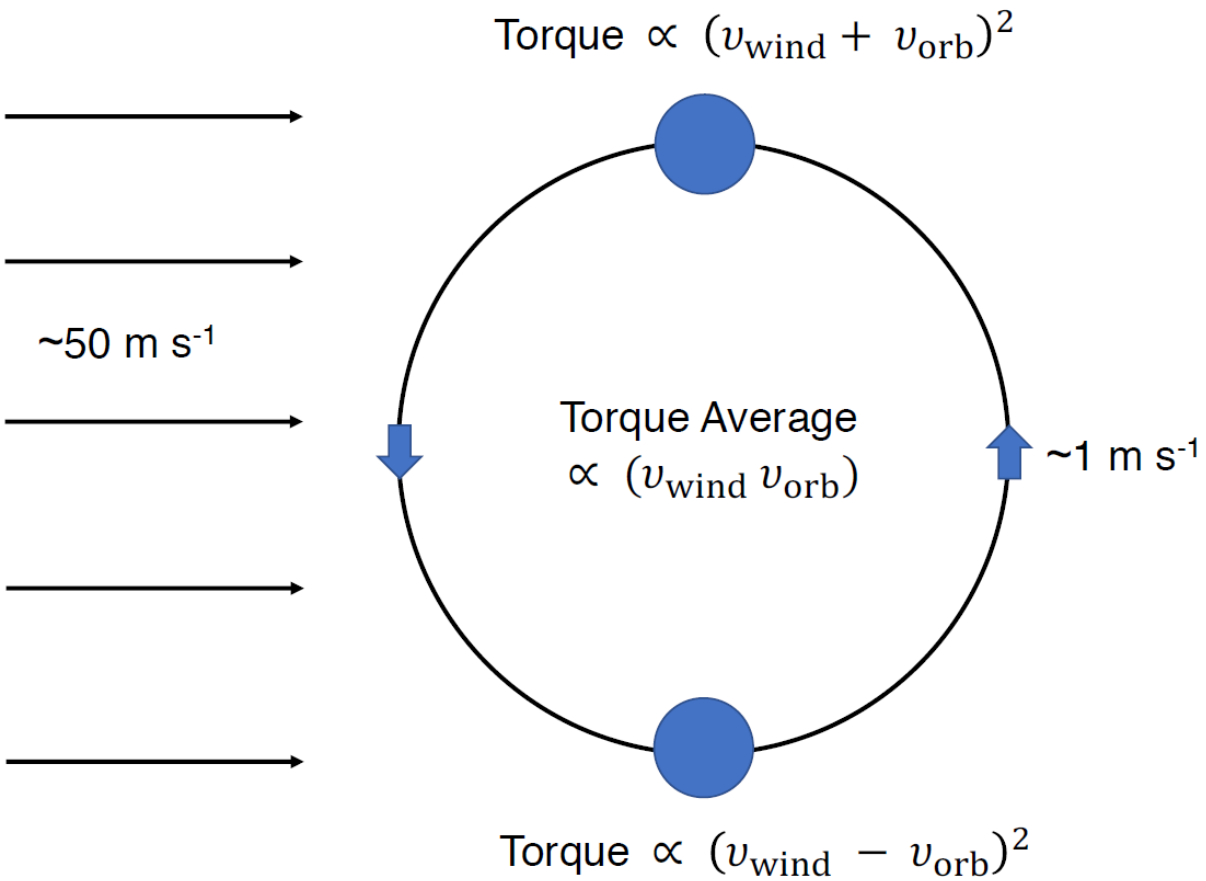
- The gravity perturbation of the third body (the sun) can generate the oscillation of eccentricity and inclination of binary spin orbits.
- During periods of high eccentricity, the binary objects pass closer to one another, and so have stronger tidal interactions. And the objects may undergo grazing collisions and dissipate kinetic energy.

Merger Mechanisms: Collisions



- Arrokoth's low crater density also makes impacts an unlikely candidate for collapsing the pair's orbit
- If we consider the largest crater (Maryland), assuming impact speed 300m/s and distantce a = 100km, the angular momentum change is approximately 10%

Merger Mechanisms: Gas Drags



$$t_{stop} \approx \frac{\rho R}{C_D \rho_{gas} v_{wind}} \approx Myr$$

- Such time scales are consistent with the short lifetimes of protoplanetary gas disks.
- Headwind-coupled gas drag may therefore be the dominant mechanism that drove the merger of small Kuiper belt binaries such as Arrokoth.

Comments

- The *New Horizons* encounter with Arrokoth has allowed the theories of cold classical Kuiper belt to be tested with close observation of a primitive planetesimal.

- Arrokoth is a contact binary, consistent with being a primordial planetesimal. There is no evidence of heliocentric, high-speed collisional evolution, or any catastrophic impact during its lifetime.

- Numerical modeling indicates that tighter or contact binaries could form in a collapsing pebble cloud. And two lobes came together at low velocity, no more than a few m/s.

- Binary mergers in the Kuiper belt indicates the potentially dominant role of gas drag while the protosolar nebula is still present.

Possible Questions

- Why are the minor axes of two lobes aligned to the spin axis?
- Does the radiation pressure from the sun dissipate the kinetic energy of the primitive binary?
- Is there any higher-multiple contact systems in the Kuiper belt?