# CO-ACCRETION + GIANT IMPACT ORIGIN OF THE URANUS SYSTEM.

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The formation of Uranus and Neptune remains poorly understood. Origin models vary significantly, from models that assume a gradual accretion of small bodies (e.g., [1]), to those that invoke a late-stage giant impact phase (e.g., [2]), in which planets form from the merger of large protoplanetary-sized bodies. The satellite systems may provide additional constraints on the final stages of ice giant formation.

The four Uranian major satellites have nearly circular, co-planar orbits and the ratio of the satellite system and planetary mass resembles Jupiter's satellite system, suggesting the Uranian system was similarly formed within a disk produced by gas co-accretion. However, Uranus is a retrograde rotator with a high obliquity. The satellites orbit in its highly tilted equatorial plane in the same sense as the planet's retrograde rotation, a configuration that cannot be explained by co-accretion alone. In this work we investigate the first stages of the co-accretion + giant impact scenario proposed by Morbidelli et al. (2012) [3] for the origin of the Uranian system (Figure 1). In this model, a satellite system formed by co-accretion is destabilized by a giant impact that tilts the planet. The primordial satellites collide and disrupt, creating an outer debris disk that can re-orient to the planet's new equatorial plane and accrete into Uranus' 4 major satellites. In order for the outer disk to realign out to Oberon's semimajor axis, an impact generated c-disk of $10^{-2}$ $M_{Ur}$ (where $M_{Ur}$ is the current Uranian mass) is required. In this work we performed impact simulations to determine whether a giant impact can both appropriately tilt Uranus and generate an inner c-disk massive enough to reorient the primordial satellite system. We find that such impacts do not produce inner debris disks massive enough to realign the outer debris disk to the post-impact equatorial plane [4] (Figure 2). Although our results are inconsistent with the apparent requirements of a co-accretion + giant impact model, we suggest alternatives that merit further exploration.

**References:**

[1] Goldreich, P. et al. (2004) *Annu. Rev.Astron. Astrophys.,* 42, 549. [2] Izidoro, A. et al. (2015) *A&A*, 582, A99. [3] Morbidelli, A. et al. (2012), *Icarus,* 219, 737. [4] Rufu R. and Canup R. M. (2022), *ApJ*, 928(2), p.123.

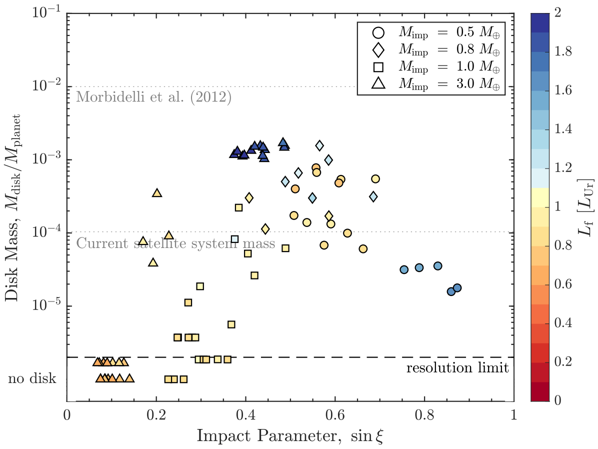

Figure 2 - Disk mass as a function of the scaled impact parameter, sin ξ, for impactor masses of 0.5 (circle), 0.8 (diamond), 1 (square) and 3 $M_\oplus$ (triangles). These simulations all had impact velocities within about 20% of Uranus' escape velocity. The colors of the markers correspond to the post-impact bound system AM, $L_f$ . The lower grey dotted line represents the mass of the current Uranian satellite. The upper grey dotted line represents the minimum disk mass required to realign the outer disk to the planet's post-impact equatorial plane [3].

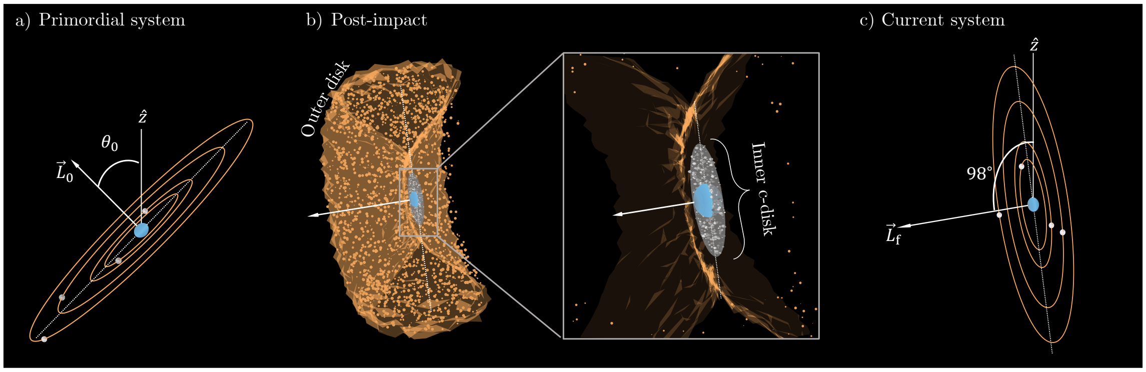

Figure 1 - Schematic of the Morbidelli et al. (2012) [3] scenario. a) Initially, Uranus has a moderate obliquity ($\theta_0$) and a regular prograde satellite system formed by gas co-accretion. b) A giant impact tilts the planet to 98° obliquity and forms an inner impact generated debris (gray disk). The impact destabilizes the primordial satellites, causing mutually disruptive collisions and creating an outer debris cloud. The outer debris disk undergoes differential nodal regression to form a torus (orange) that is symmetric about Uranus' new equatorial plane (white dashed line). c) Uranus' satellites re-accrete from the outer disk on low inclination orbits, while essentially all of the inner c-disk and its byproducts are lost to collision with Uranus.