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Co-accretion + impact origin of the Uranian satellites?

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Abstract

We consider the origin of the Uranian satellites in a scenario proposed by Morbidelli et al. [6], in which an initial satellite system produced by co-accretion is disrupted by mutual collisions as a result of a Uranus tipping giant impact. Debris from the primordial system re-orients to Uranus's new equatorial plane via interactions with a massive inner *c-disk* produced by a Uranus tilting giant impact, after which time the Uranus satellites re-accrete in their current orbits. A massive c-disk with ~1% of Uranus's mass is needed to achieve the needed realignment and account for outermost Oberon's low inclination orbit [6]. In the co-accretion + giant impact model, the inner c-disk and its byproducts must eventually be lost to inward tidal evolution. We simulate the evolution of this c-disk, including viscous spreading and its interactions with re-assembled outer Uranian moons. We find that the c-disk creates large inner moons that typically destabilize the outer satellites, and that massive, long-lived inner moons inconsistent with the current system can also result.

1. Introduction

The origin of the Uranian satellites remains poorly understood. Yet, this system may provide additional clues to the early history of the ice giants, and help constrain various formation mechanisms (e.g. [4, 5, 7]). The main Uranian satellites have nearly circular, co-planar orbits, with semi-major axes between 5 and 23 Uranian radii (R_U) and a total mass of about 10^{-4} Uranus masses (M_U). In these respects the Uranus system resembles that of Jupiter. But Uranus is a retrograde rotator with an obliquity of 98°, and its satellites orbit in its highly tilted equatorial plane and in the same sense as its retrograde rotation.

[6] proposed that early Uranus had a primordial satellite system produced from co-accretion (e.g. [2]). The planet was subsequently tilted by a giant impact, during which a massive inner c-disk was formed around the planet interior to the Roche limit. The impulsive effects of the giant impact caused the primordial moons to collide and disrupt, forming an outer debris disk that was initially highly inclined relative to Uranus's post-impact equatorial plane. However if the inner c-disk was sufficiently massive, with $\geq 10^{-2} M_U$ [6], differential nodal regression of the outer debris disk would have been sufficient to re-orient it to Uranus's new equatorial plane. The current satellite could then re-accrete from this outer debris disk on their observed low-inclination orbits.

While this scenario offers a promising explanation for the Uranian system, a key open issue is the fate of the inner c-disk. A massive c-disk would spawn massive inner moons [8, 9], and yet no massive ring nor massive inner moon(s) exist at Uranus today. [6] suggested that the c-disk and any moons spawned from it remained interior to synchronous orbit (currently at 3.3R_U) and were thus lost to inward tidal evolution. However, models of the evolution of a Roche-interior disk find that the combination of disk interactions and capture of spawned moons into mutual mean-motion resonances can lead to substantial orbital expansion [1, 8, 9]. This could result in the survival of large moons spawned from the c-disk that are not seen today. In addition, the formation and evolution of large inner moons could destabilize the outer satellite system that accumulated from the outer debris disk.

2. Model

We investigate the dynamics of an initial system in which the current rock-ice outer moons (Ariel, Umbriel, Titania, and Oberon) have re-accumulated from the outer debris disk before the c-disk has cooled and condensed. The re-accumulation timescale in the outer disk is $\leq 10^4$ yr. The post-impact c-disk is expected to contain primarily vaporized water, and Uranus's luminosity will maintain it in a vapor state for > 10^4 to 10^5 yr. As the c-disk cools and condenses, we consider that it will have a viscosity driven by local gravitational instability in the melt. The magnitude of this viscosity is regulated by the cooling rate from the disk's photosphere [10, 11], resulting in an initial c-disk spreading timescale of ~10^6 years.

We use a modified version of the N-body integrator SyMBA [3] to which we have added an analytical prescription for a uniform surface density disk that spreads viscously and interacts with outer moons at the strongest Lindblad resonances [1, 8, 9]. As the disk spreads beyond the Roche limit ($a_R \sim 2.7R_U$), new moonlets are spawned and added to the N-body code. We also include tidal dissipation, resulting in orbital contraction (expansion) of moons located inside (outside) the synchronous orbit, which we place at $a_{sync} \sim 4-5R_U$ to correspond to a not yet fully contracted Uranus.

3. Results

Figure 1 shows the evolution of a system with an initial c-disk with $3 \times 10^{-3} M_U$ and the 4 major moons with their current positions and masses. We assume tidal parameters for Uranus of $(Q/k_2) = 10^4$, a planet with radius $1.3R_U$, and $a_{sync} = 4.5R_U$.

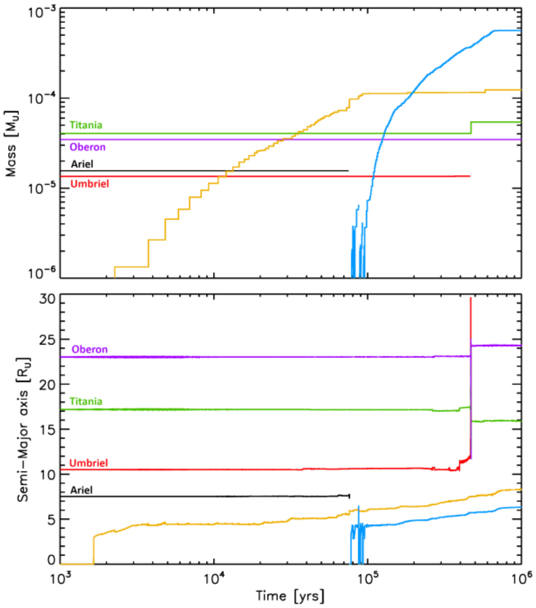

Figure 1: Masses and semi-major axes of the largest bodies in the simulation. The black, red, green and purple lines show the Ariel, Umbriel, Titania and Oberon equivalents. The orange and blue curves show two additional moons growing from the c-disk. These large moons destabilize the outer moons by either absorbing them, or crossing their mean-motion resonances, causing them to collide with each other.

After $\sim 1.5 \times 10^3$ years, a large moon rapidly grows near the Roche limit. Its semi-major axis expands to $4.3R_U$, at which point its 2:1 resonance lies at the c-disk's outer edge. At this point, additional moonlets form, and as some of them get captured in mean-motion resonances (MMR) they drive the first large moon outward in lock-step. After $\sim 8 \times 10^4$ years, the first large moon absorbs the Ariel-analog. Similar processes continue on longer timescales until the Umbriel-analog captures an inner moon into a MMR. Its semi-major axis then expands and it merges with the Titania analog at $\sim 4.5 \times 10^5$ years. At the end of the simulation, two very massive moons with masses $1.2 \times 10^{-4} M_U$ and $5.6 \times 10^{-4} M_U$ have formed from the inner c-disk. These moons will be long lived because their semi-major axes lie beyond a_{sync}. We consider what modifications could allow for more successful outcomes, including faster tidal evolution.

Acknowledgements

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