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Explaining why the satellites of Uranus have equatorial prograde orbits despite of the large planet's obliquity.

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Abstract

We show that the existence of equatorial satellites is not inconsistent with the collisional tilting scenario for Uranus. In fact, if the planet was surrounded by a proto-satellite disk at the time of the tilting and a massive ring of material was temporarily placed inside the Roche radius of the planet by the collision, the proto-satellite disk would have started to precess incoherently around the equator of the planet. Collisional damping would then collapse it into a thin equatorial disk from which the satellites eventually formed. The fact that the satellites are prograde requires that Uranus already had a non-negligible obliquity (comparable to that of Neptune) when it was finally tilted to 98 degrees.

1. Introduction

The origin of the large obliquity of Uranus remains elusive. Two scenarios have been proposed: an impulsive tilt due to a collision with a massive body [1] or a slow tilt due to a resonance between the precession rates of the spin axis and the orbit [2].

A critical constraint is that the regular satellites of Uranus have essentially equatorial orbits and they are prograde relative to the rotation of the planet. Notice that the rotation of the planet is, strictly speaking, retrograde, as Uranus obliquity is about 98 degrees.

In this work we explore which scenario for the origin of Uranus obliquity can explain the equatorial prograde orbits of its satellites.

2. Slow-tilting by spin-orbit resonance

In principle, if the satellites were originally on the equator of Uranus and the planet was tilted slowly, the satellites would have preserved equatorial orbits by adiabatic invariance. The Laplace plane is in fact very close to the equator, for all bodies up to Oberon's distance, due to the oblateness of the planet.

However, to have a resonance between the precession rate of the spin axis of Uranus and the secular frequency of precession of its orbit (as required to tilt the planet slowly), the former had to be much faster than now. In [2] this is achieved by assuming that Uranus had originally a massive satellite with an orbital radius of about 0.01 AU (Satellite X, hereafter). The problem is that the Laplace plane for Satellite X is close to the orbital plane of Uranus. Thus, Satellite X would not follow the equator during the tilting of the planet and, by its large mass, it would retain the other satellites (particularly Titania and Oberon) on its own orbital plane. When Satellite X is removed by chaotic dynamics, the tilting process is over. The regular satellites of Uranus would be off equator, like in an impulsive tilting scenario.

3. Collisional, impulsive tilting

If Uranus had been tilted abruptly to its current obliquity, the satellites would have become unstable. They would have collided with each other and presumably generated a debris disk. However, it is likely that the giant collision that tilted Uranus occurred during the accretion phase of the planet, when satellites were not formed yet and the planet was surrounded by a tenuous disk of gas, very rich in solids, like it is usually invoked for the formation of satellites around giant planets [3]. Thus, we develop our scenario for a planetesimal disk, extended up to slightly beyond the distance of Oberon, and with a total mass between 1 and 2 times the mass of the five regular satellites altogether. We call this the proto-satellite disk. We neglect gas, in first approximation.

When the planet is tilted, the proto-satellite disk breaks in two parts. In the inner part, the orbits of the planetesimals precess with constant inclination around the equator of the planet and with precession rates that depend very sensitively on the distance. Upon time, the nodal phases are randomized and a torus is formed, symmetric with respect to the equator. Collisional damping would cause the planetesimals to collapse onto an equatorial disk.

Instead, the outer part the proto-satellite disk, under the effect of its own self-gravity, would precess rigidly around the equator. Collisional damping would make this disk thinner with time, but would not produce an equatorial disk.

For the current J_2 of the planet, the boundary between the inner and outer parts of the proto-satellite disk would be located near the current orbital radius of Miranda. Thus, we cannot explain the equatorial orbits of the more distant satellites, such as Titania and Oberon.

However, simulations of the collisional tilting of Uranus show that the impact should have generated an equatorial disk of debris, accounting for 1 to 3% of the mass of Uranus, namely about 100 times more massive than the proto-satellite disk, but mostly confined within 3 Uranian radii [4]. We call this disk, equivalent to the proto-Lunar disk, the C-disk, as it was generated in the collision.

The C-disk could *not* generate the current regular satellites of Uranus, because the latter are too far away [5]. In fact, most likely, as the C-disk spread outside of the Roche lobe of the planet, it formed satellites [6] which, being situated inside the corotation radius, migrated by tides into the planet. The existence of the C-disk (or of the close satellites that it generated), however, is equivalent to increasing the planet's J2 enormously.

Consequently, the boundary between the inner and outer parts of the proto-satellite disk would have been situated beyond Oberon's orbital radius. Thus, collisional damping would have created an equatorial disk up to Oberon's distance, from which the current regular satellites eventually formed.

We tested this scenario with both analytic calculations and numerical simulations, the latter accounting for self-gravity in the proto-satellite disk and implemented on GPU machines.

4. Why are Uranus satellites prograde?

If Uranus had been tilted abruptly from 0 to 98 degrees obliquity, the mechanism described in the previous section would have produced a system of equatorial, but retrograde satellites.

To have the disk collapse by collisional damping onto an equatorial, *prograde* disk, it is necessary that the obliquity of Uranus was not null when the planet's last tilt occurred.

We have computed, with a MonteCarlo calculation, the probability that the final proto-satellite disk is prograde as a function of the initial obliquity of Uranus. We find that the probability increases rapidly with the obliquity and, for an obliquity of 30° (like that of Neptune), it is about 40%.

5. Conclusions

We conclude that the collisional tilting scenario for Uranus is consistent with the equatorial character of the orbits of its regular satellites.

The fact that the satellites are prograde, implies that Uranus was not tilted in one shot from 0 to 98 degrees. It had to have a non-negligible obliquity before the last giant impact.

This result, together with the obliquity of Neptune, suggests that giant impacts, affecting the obliquities, have been rather common during the growth of the ice-giant planets of the solar system. Thus, these planets presumably did not grow by simple runaway/oligarchic accretion of planetesimals, but experienced also a phase of giant impacts with planetary embryos, similar to the one characterizing terrestrial planet formation.

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