The Origin of Saturn’s Obliquity and Young Rings

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What is so Unusual About Planet Saturn?
How did Saturn become the Lord of the Rings?

GAS GIANT PLANETS

Loss of a satellite could explain Saturn’s obliquity and young rings

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What is so unusual about Planet Saturn?

Gravity field measured
Winds are 9000 km deep.
Rings are only 100 million years old.
Mass of Saturn’s Rings Measured
Directly from the gravity signal, we determined a total mass of the main rings A, B and C =

\[ 0.41 \pm 0.13 \text{ Mimas masses.} \]

(2000 Mimas masses = 1 lunar mass)
(16000 Mimas masses = 1 Earth mass)
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An indication that the rings are young, were formed only 10-100 million years ago.

What is a Cassini State?

Answer: Spin-Orbit Coupling between Planets or Moons
Example for Cassini State: Mercury’s Orbit Around the Sun
Spin-Orbit Coupling
What is a Cassini State?

In 1643 Giovanni Cassini discovered spin-orbital coupling in the moon’s motion.

The following three vectors always lie in one plane:
1) Vector normal to Earth’s orbit around the sun.
2) Vector normal to the orbit of the moon around Earth
3) Spin axis of the moon

The moon regresses with an 18.6 year period. The so-called Cassini state is an example of a secular spin-orbit resonance.
This Saturn in Resonance with Neptune? This depends on Saturn’s Angular Momentum

Precession constant: \( \alpha = \frac{3}{2} \frac{n}{\omega} \left( \frac{J_2 + q}{\lambda + l} \right) \)

Saturn’s moment of inertia: \( C/MR^2 \)

Moons’ contribution to angular momentum

Torques acting on Saturn

Torques acting on moons’ orbits including Titan

Saillenfest (2021)
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Moons’ contribution to angular momentum

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Why do $J_2$, $J_4$, and $J_6$ constrain the moment of inertia so well?

\[ J_n = -\frac{2\pi}{Ma^n} \int_{-1}^{1} d\mu \int_{0}^{a} r^{n+2} P_n(\mu) \rho(r, \mu) dr \]

\[ \text{MoI} \equiv \frac{C}{MR_e^2} = \frac{2\pi}{MR_e^2} \int_{-1}^{1} d\mu \int_{0}^{+1} d\mu \int_{0}^{R(\mu)} r^2 l^2 \rho(r, \mu) \]
Our scenario for the formation of Saturn's rings

1. The Saturnian system formed with an additional moon, Chrysalis. Saturn's spin axis was perpendicular to its orbital plane.
2. Chrysalis gave Neptune an extra "handle" to tilt Saturn's spin axis (via a spin-orbit resonance) to the large value that we see today, 27°.
3. Saturn's moon Titan started to migrate out. About 160 million years ago, it entered into a resonance with the moon Chrysalis destabilizing its orbit.
4. As a result, Chrysalis came so close to Saturn that it was sheared apart by Saturn's intense gravity (tidal disruption). Most of the material fell into Saturn but out of 1%, the rings formed.
5. With Chrysalis gone, Neptune could no longer change Saturn's spin axis. So the planet was left spinning at an angle of 27°.
Our scenario for the formation of Saturn's rings is supported by the following lines of evidence:

1. It predicts a young age for **Saturn's rings of only 100 million years** approximately. This is in agreement with the ring color and Cassini's measurements of the ring mass.
2. It explains **why Saturn's spin axis is tilted** rather than being vertical, which it was when the planet formed.
3. It also explains **why Saturn's moment of inertia is so close to the critical value** to be in a spin-orbit resonance with Neptune but just outside of the critical region.
4. It is consistent with **Titan's observed migration** and offers an explanation why its orbit is slightly elliptical.
Any Questions?