
Did Saturn's rings
form during the
Late Heavy Bombardment ?
Charnoz, Morbidelli, Dones and Salmon.
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Did Saturn's rings form during the LHB ?

1. A few rings characteristics
2. Origins scenarii
3. Impactor flux history
4. Viability of the formation models
5. Models evaluation

1. A few rings characteristics

- Saturn's main rings mass = a few Mimas masses (Esposito, 1983)
- Almost pure water ice
- Saturn is the only planet having such a ring system

2. Origins scenarii

1. Tidal splitting of a massive object:

A massive comet (or a Centaur object) was tidally disrupted during a close and slow encounter with Saturn (Dones, 1991).

2. Origins scenarii

<u>2. Collisional destruction of a satellite</u>

A satellite was originally in Saturn's Roche Zone and was destroyed by a passing comet (Pollack, 1973).

2. Origins scenarii

<u>3. Remnants of Saturn's sub-nebula disk</u>

(Pollack, 1973)

Less popular : composition difference between rings and classical satellites, whereas they should have originated from the same disk on this scenario.

2.3. Age of the rings

Rapid evolutionnary processes suggest young ring system (maybe < 10^8 yrs old).

But, both scenario 1 and 2 require the passage of one or several big comets very close to Saturn.

Current rate of passing comets is too low.

Viscosity under-estimated and new evidence of propellers and strange-shaped satellites denser than ice : present during rings formation → LHB.

2.3. Age of the rings: Pan/Atlas

From Charnoz, 2007.

3. Impactor flux history

3.1. The LHB as predicted by the Nice Model

3.2. Impact rates from the model

3.3. Impactors size distributions

3.1. The Nice model (Tsiganis, Morbidelli, Gomes, 2005)

Reproduces :

- Orbital architecture of the giant planet system
- Capture of Jupiter's and Neptune's Trojans
- Current structure of the Kuiper Belt
- Capture of irregular satellites of Saturn, Uranus and Neptune
- Late Heavy Bombardment

Parameters:

- Giant planets on nearly circular and coplanar orbits (from 5.5 to 14 AU)
- Saturn inside the 1:2 MMR
- Planetesimal disk (14 to 34 AU), m = 35 Earth masses

3.1. The Nice model

Planetesimals at the inner edge of the disk evolve into Neptune-scattering orbits in a few Myrs.

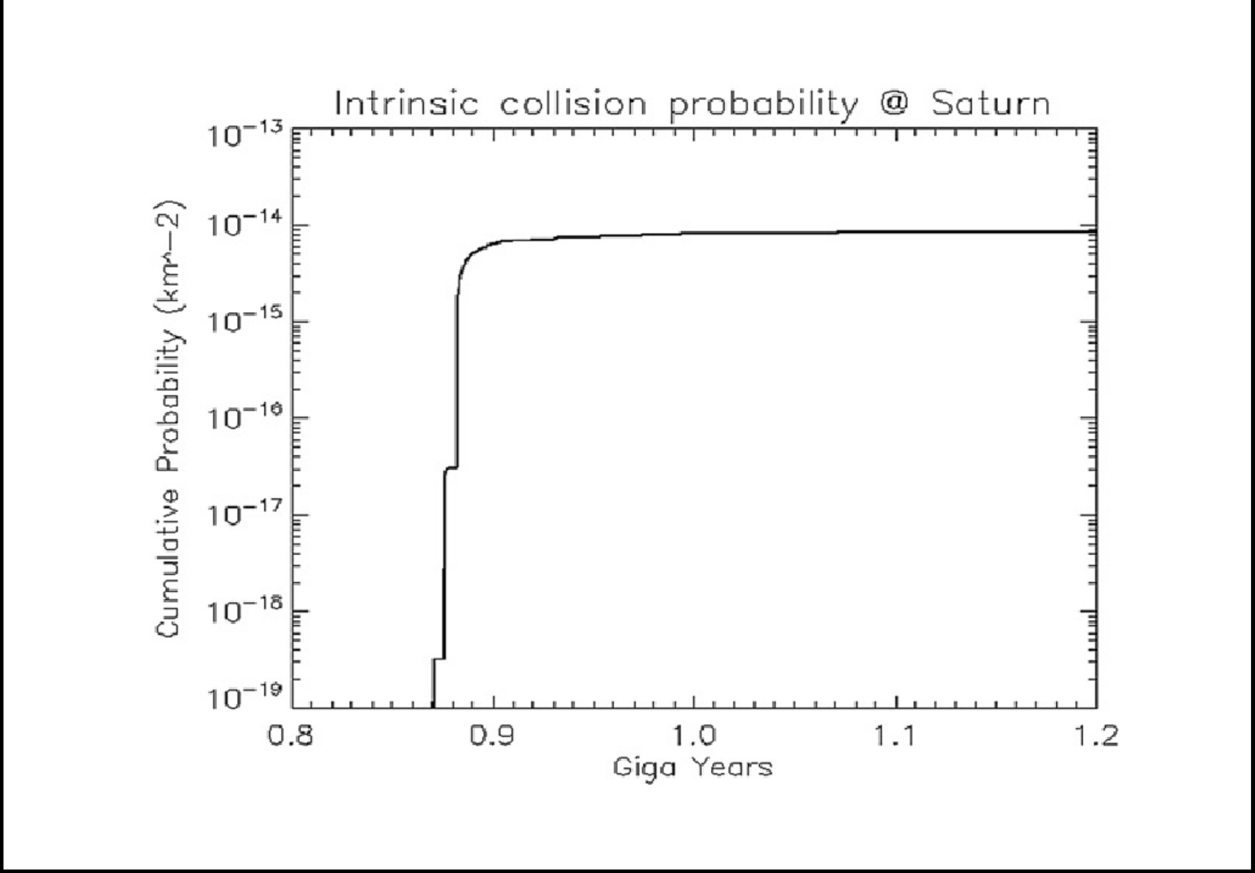
Migration of the giant planets governed by the planetesimal escape rate from the disk until disk particles are removed.

Jupiter and Saturn cross their mutual 1:2 MMR: Uranus and Neptune gain e, penetrate into the disk → LHB ~ 700-900 Myrs after planet formation

e damped in a few Myrs and Jupiter and Saturn decouple

3.2. Impact rates

Cumulative mean intrinsic impact probability per particle at Saturn derived from Nice simulations.



LHB occurs here at 850 Myr and lasts 50 Myr until stationnarity.

3.3. Impactors size distribution

Impactors in Saturn's system come from the primitive trans-neptunian disk (Nice model).

Size distribution is derived from the Kuiper Belt in Charnoz, 2007.
KB $<$ 0.1 M(Earth)
SD $\sim$ 20 M(Earth)

Mass depletion due to dynamical processes.
Primordial distribution = present * size-dependent factor.

Rescaling with crater records of Iapetus (believed to be Saturn's satellite with the oldest surface).

3.3. Impactors size distribution

Size distribution of the projectiles on Saturn's system:

$$\frac{dN}{dr} \propto r^{-4.5}\ ,\ for\ r > 100\ km$$

$$\frac{dN}{dr} \propto r^{-3.5}\ ,\ for\ 7.5\ km < r < 100\ km$$

$$\frac{dN}{dr} \propto r^{-2.5}\ ,\ for\ r < 7.5\ km$$

With this distribution, 13 (D>300 km)-craters can be expected on Iapetus vs 10-15 observed, and 800 Pluto-sized bodies can be expected.

4. Viability of the formation models

4.1. Tidally disrupted comets

4.2. Collisional destruction of a primordial satellite

4.1. Tidally disrupted comets

Comets passing on hyperbolic orbits inside Saturn's Roche's zone with a low asymptotic velocity are tidally disrupted.

Some comet fragments captured.

Collisions → orbits circularized, fragments grinded to smaller sizes, and disk flattened.

4.1. Tidally disrupted comets

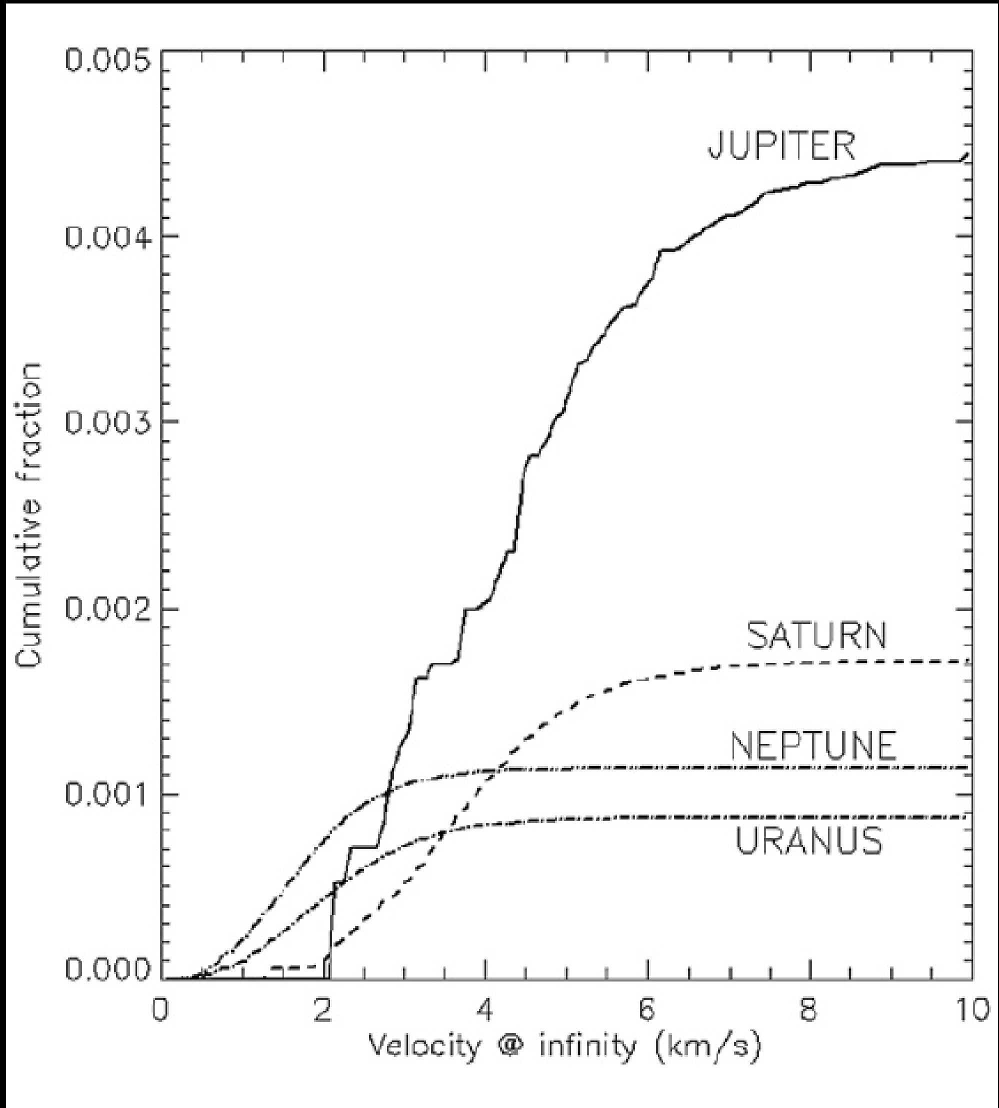
Fraction of cometary material captured on an orbit with apocenter < R_{stab}

$$f = \frac{0.9\Delta E - GM_S / R_{stab} - 0.5V_\infty^2}{1.8\Delta E}$$

where $\Delta E = GM_S r_c / q^2$, for a comet a radius r_c, which closest distance to the center of the planet is q.

$R_{stab} < R_{Hill}$

$M_{captured} \sim 36\ M_{Mimas}$, mainly in a few very massive events with very low probability

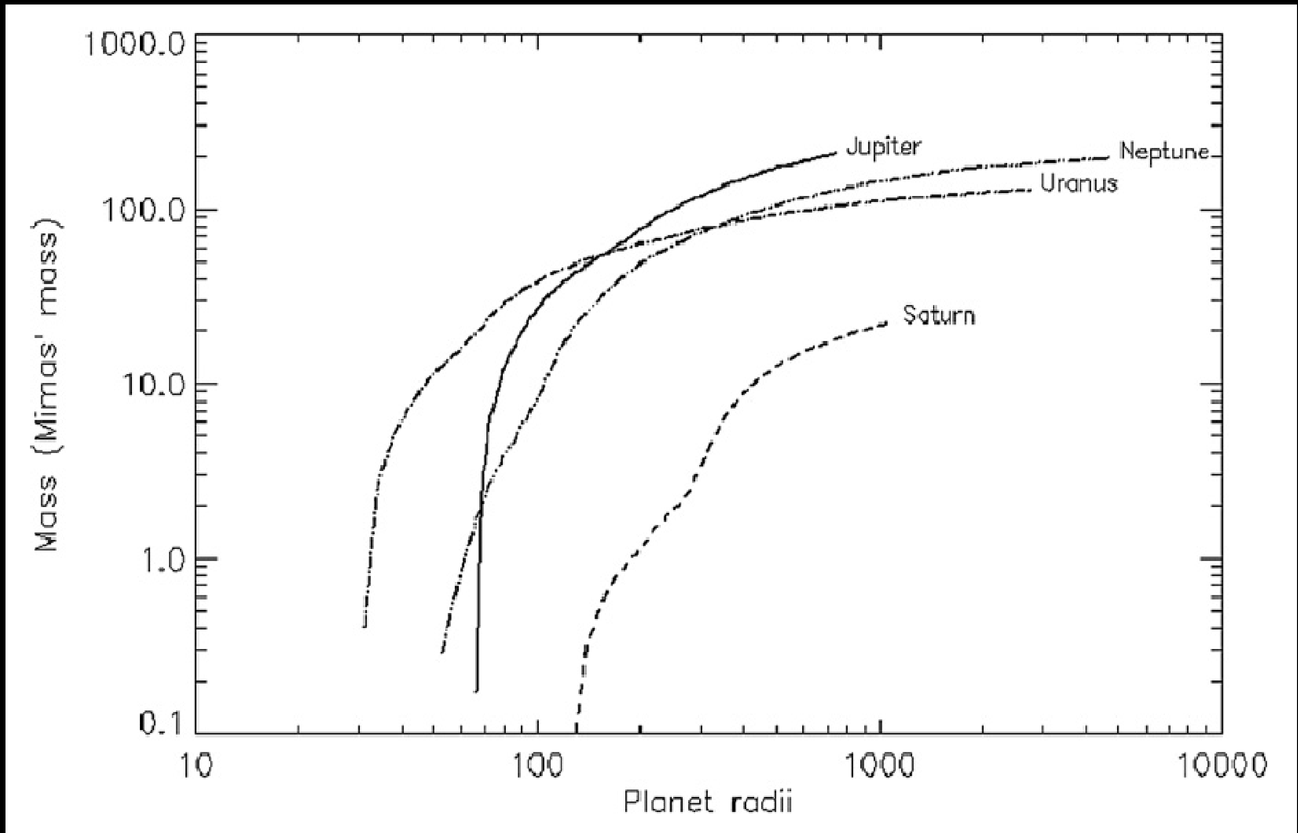


4.1. Tidally disrupted comets

Saturn captures the smallest amount of material !

All giant planets should have acquired massive rings.

Distribution of apocenters (total mass of cometary debris with orbit apocenter < given R) for material injected in the planet's Hill sphere.



4.1. Tidally disrupted comets

Possible explanations:

- Domination of a few rare events involving massive objects
- Lots of captured fragments have an e > 0.9 Difficult to predict survival to tiny perturbations
- Dones (1991) : incoming body breaks in infinite number of particles.

  Dobrolovskis (1990) : main fracture → few big objects
- Uranus, Neptune and Jupiter's rings may be destroyed in less than 4.5 Gyrs

But still they are all prograde – numerical simulations suggest equal probability for prograde and retrograde.

4.2. Collisional destruction of a primordial satellite

M_{rings} M_{Mimas} → rings = break-up of ancient satellite ?

Constraints:

- Such a satellite (r 200 – 400 km) should be brought inside Roche radius.
- Survival in the Roche Zone until the LHB
- Impact probabilities

4.2. Collisional destruction of a primordial satellite

Implanting a satellite in Saturn's Roche Zone

Canup model of satellite formation in circumplanetary disks:

- Total satellite system mass 1500 M_{Mimas}
- Late formation of surviving satellites: inward migration in the circumplanetary disk may result in collision onto the planet. The satellite keeps the orbit it reached when migration stopped.

4.2. Collisional destruction of a primordial satellite

Tidal interactions with the planet after migration (10 Myrs). 700 Myrs to survive tidal splitting and tidaly driven migration.

<u>Surviving tidal splitting in Saturn's Roche Zone</u>

A Mimas-like satellite could survive tidal splitting (cf Amalthea inside Jupiter's Roche Zone, Pan, Daphnis inside Saturn's RZ, Naiaid, Thalassa, Despina, Galatea and Larissa inside Neptune's RZ).

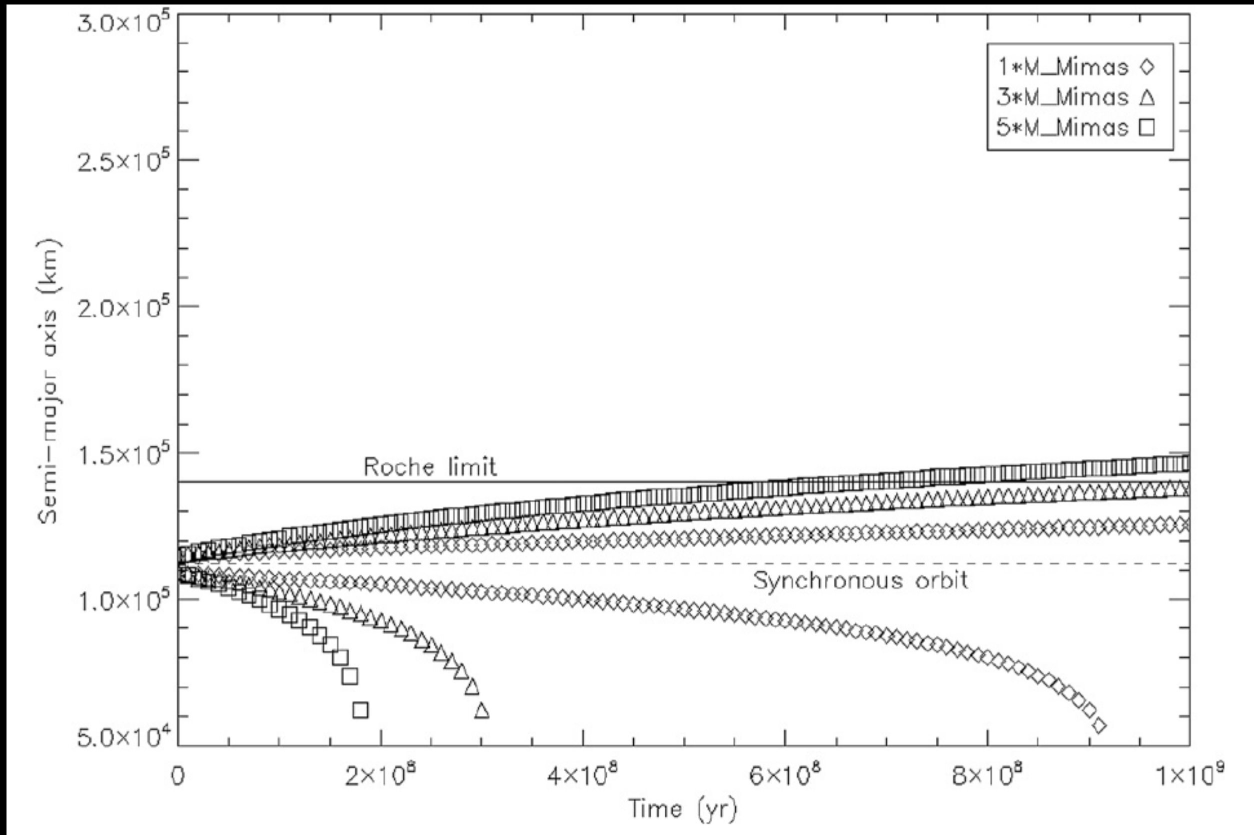
Another process is required to generate the ring.

4.2. Collisional destruction of a primordial satellite

Surviving tidally driven migration in Saturn's Roche Zone

Tidal migration inward if a_{sat} < a(Sync orbit) and outward otherwise.

A satellite starting inside the Synchronous orbit falls onto the planet before the LHB, but a satellite starting between the Sync orbit and the Roche radius can survive up to the LHB.



Charnoz et al., 2009

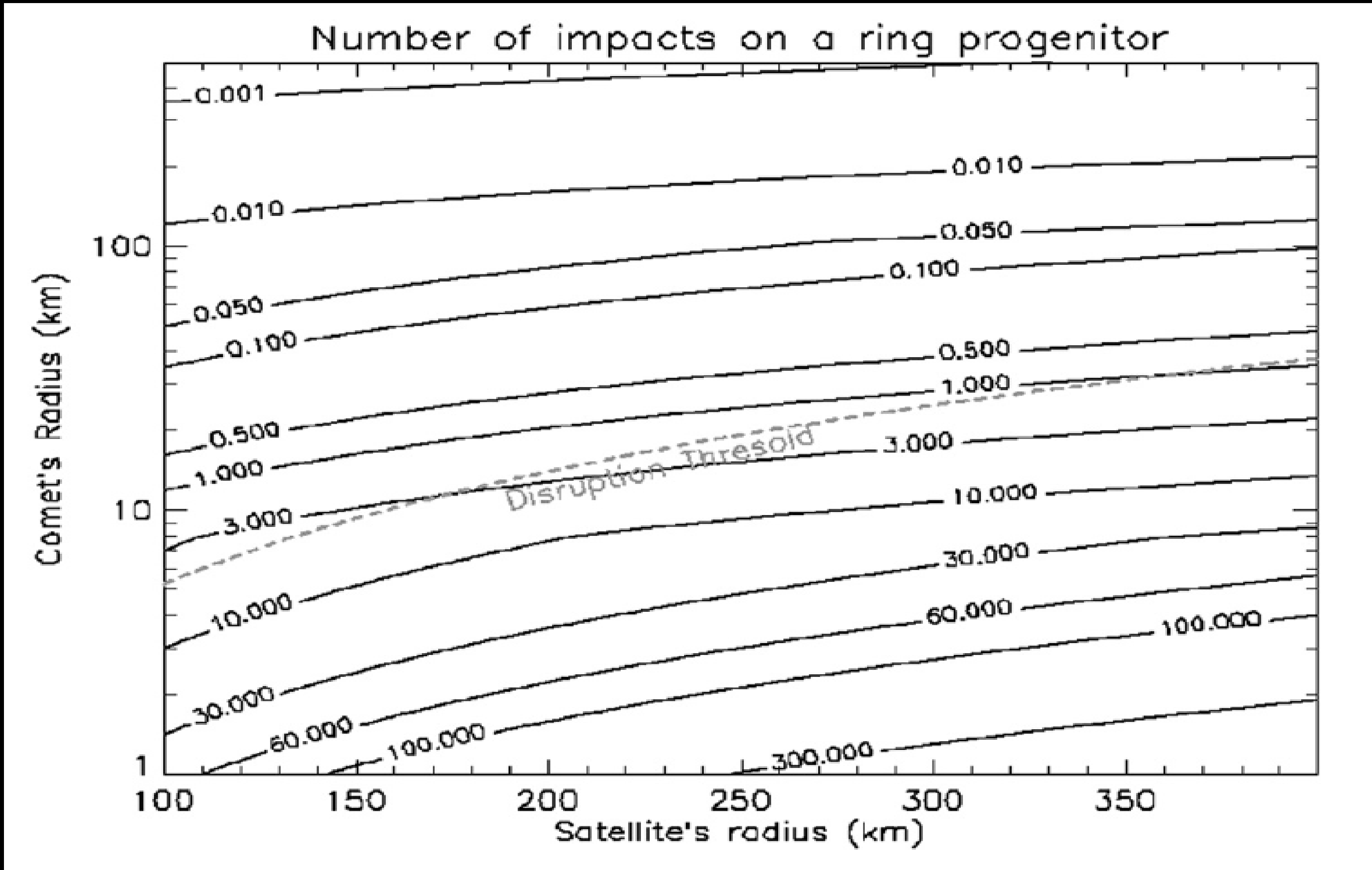
4.2. Collisional destruction of a primordial satellite

Note that R(sync orbit) ~ R(B ring), the most massive : the putative satellite may have been destroyed there.

Hydrocode simulations : at 32 km/s

- 200 km satellite (1 M_{Mimas}) destruction requires a 17 km impactor
- 300 km satellite (3 M_{Mimas}) destruction requires a 31 km impactor
- 350 km satellite (5 M_{Mimas}) destruction requires a 39 km impactor

4.2. Collisional destruction of a primordial satellite



Number of comet impacts during the LHB for a satellite at 100,000 km from Saturn.
The disruption line shows the minimum comet size for disruption in a single impact.

4.2. Collisional destruction of a primordial satellite

A satellite of a few Mimas masses located inside the Roche Zone could have been destroyed during the LHB with a substantial probability.

Scattered fragments orbit inside the RZ and cannot reaccrete. Formation of a disk of mass comparable to the parent body's mass.

4.2. Collisional destruction of a primordial satellite

Number of destructions per satellite

Table 3
Number of destructions of Saturn's satellites during the LHB, using different disruption models with the Iapetus-scaled size distribution of the primordial Kuiper Belt population (see Fig. 2).

Name	Distance (km)	Radius (km)	Number of disruptions: B&A model[a]	Survival probability B&A model	Number of disruptions: Melosh crater model[b]	Survival probability Melosh model	Number of disruptions: Zahnle crater model[c]	Survival probability Zahnle model
Ring progenitor	100,000	320	1.02	0.36	4.07	0.017	7.09	0.00083
Pan	133,583	14	3.13	0.044	37.37	0	25.15	0
Atlas	137,700	15	2.97	0.051	32.25	0	22.19	0
Prometheus	139,400	43	2.62	0.073	20.86	0	18.29	0
Pandora	141,700	40	2.58	0.076	19.98	0	17.26	0
Epimetheus	151,400	56	2.28	0.10	11.42	0	10.72	0
Janus	151,500	89	2.19	0.11	10.63	0	11.08	0
Mimas	185,600	198	0.73	0.48	3.04	0.05	4.46	0.011
Enceladus	238,100	252	0.34	0.71	0.62	0.54	0.992	0.37
Telesto	294,700	12	1.08	0.33	4.31	0.013	2.86	0.057
Calypso	294,700	10	1.10	0.33	3.92	0.020	2.52	0.08
Tethys	294,700	533	0.08	0.92	0.28	0.75	0.59	0.55
Dione	377,400	561	0.05	0.95	0.098	0.91	0.21	0.81
Rhea	527,100	764	0.01	0.99	0.039	0.96	0.10	0.90
Hyperion	1,464,099	146	0.06	0.94	0.74	0.47	0.87	0.41
Titan	1,221,850	2575	0.00013	0.9998	0.00011	0.999887	0.00062	0.9994
Iapetus	3,560,800	736	0.00112	0.9988	0.0061	0.993924	0.019	0.9806
Phoebe	12,944,300	110	0.019	0.981	0.07	0.932	0.085	0.9184

[a] The specific destruction energy is taken from Benz and Asphaug (1999); destruction is defined so that the mass of the largest fragment is less than 50% of the parent's body mass.
[b] Crater with same diameter as the parent body, using the crater scaling law of Melosh (1989).
[c] Crater with same diameter as the parent body, using the crater scaling law of Zahnle et al. (2003). Survival probabilities are computed according to Eq. (12). Note that the survival probability is simply exp(−Number of Disruptions), see Section 5.2.3.

Iapetus, Titan, Phoebe (captured?), Dione, Rhea and Thetys would probably survive. Enceladus ? Mimas and inner satellites should have been destroyed (reaccretion after the LHB?)

5. Models evaluation

The problem of silicates:

Both satellites and comets have a much larger silicates/ice ratio than observed in the rings.

However, big satellites can be differentiated.

Tidal disruption: preferential capture of surface and mantle material (high ice/Si ratio). Si core lost to unbound orbit.

Satellite destruction: intense cometary flux can peel off the icy shell of a differentiated satellite. Si core corotating with an inner and outer rings. Unstable: removes debris from the RZ.

5. Models evaluation

Massive rings around other giant planets:

Tidal disruption: capture rate is the lowest for Saturn. Survival of the other ring systems over the age of the Solar System.

Satellite destruction: only Jupiter and Saturn have their Synchronous Orbit below their Roche Limit. Neptune's inner satellites are problematic (hyp: disrupted beyond Roche Limit, reaccreted and tidally migrated inward to present locations). Jupiter's region between RL and SO is much narrower than Saturn's. But Jupiter's satellite ice/silicates ratio is lower, narrowing again the « interesting » region (exception: Amalthea is much lighter than the Galilean's satellites).

Conclusion

Tidal disruption can be part of the story but not the full story.

No obvious solution for the silicates problem.

Satellite destruction seems more probable to explain why Saturn's ring system is unique.

The LHB is the « sweet moment » for formation of a massive ring system around Saturn.