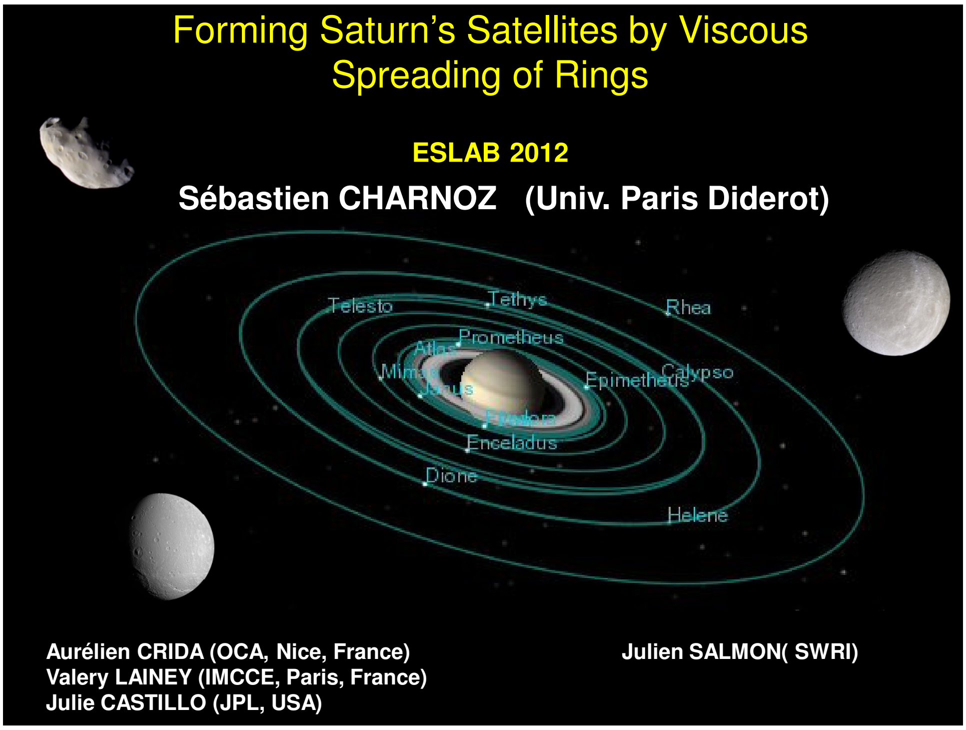
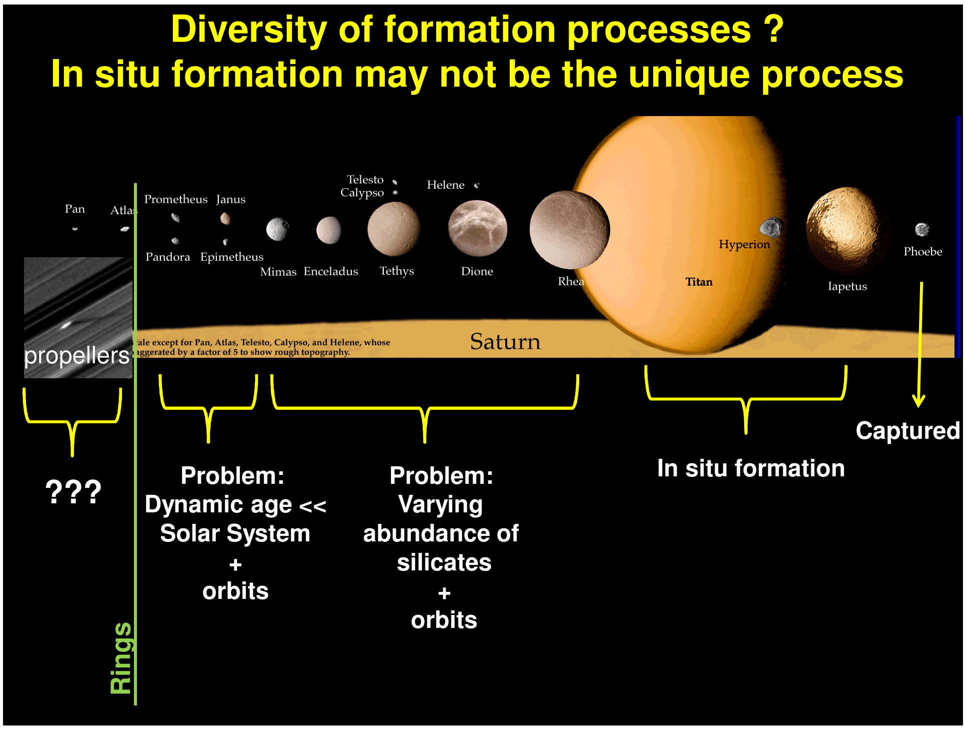
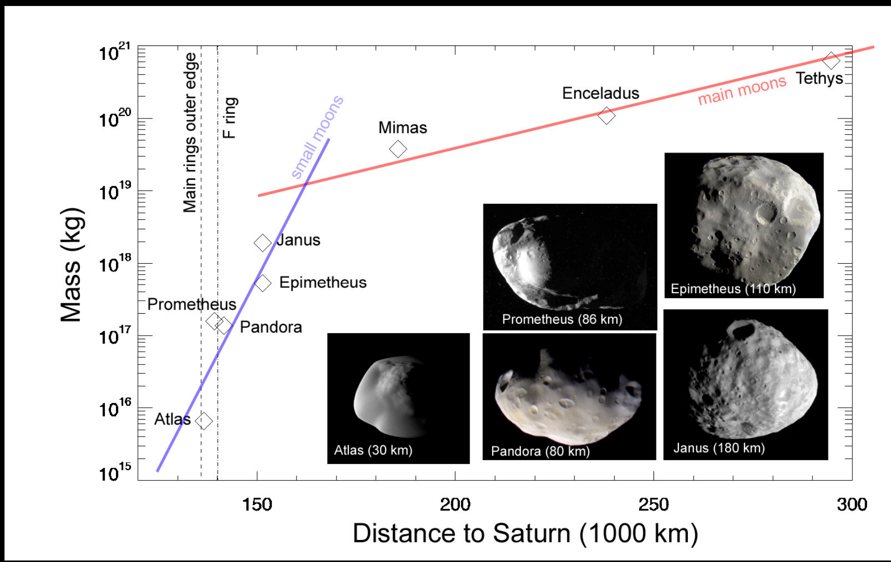
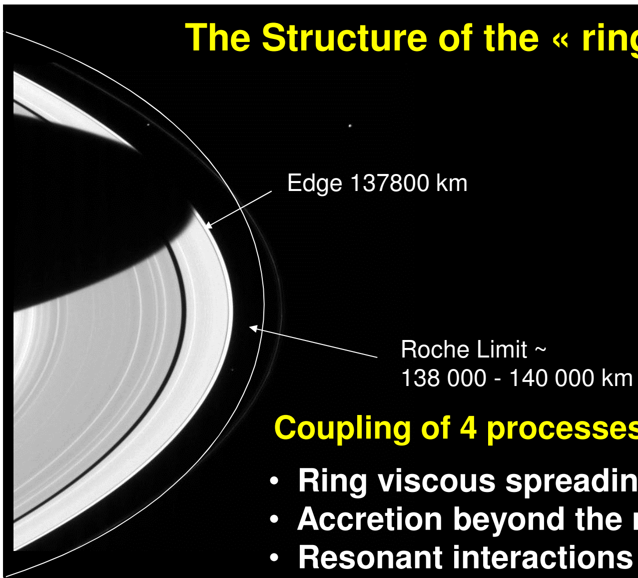

Forming Saturn's Satellites by Viscous Spreading of Rings
ESLAB 2012
Sébastien CHARNOZ (Univ. Paris Diderot)
Telesto
Tethys
Rhea
Prometheus
Atlas
Mimas
Janus
Epimetheus
Calypso
Enceladus
Dione
Helene
Aurélien CRIDA (OCA, Nice, France)
Valery LAINEY (IMCCE, Paris, France)
Julie CASTILLO (JPL, USA)
Julien SALMON(SWRI)

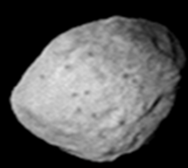

Diversity of formation processes ?
In situ formation may not be the unique process
Pan
Atlas
Prometheus
Janus
Pandora
Epimetheus
Telesto
Calypso
Helene
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Saturn
propellers
???
Problem:
Dynamic age <<
Solar System
+
orbits
Problem:
Varying
abundance of
silicates
+
orbits
In situ formation
Captured
Rings

A peculiar orbital architecture



The Structure of the « ring's edge » region



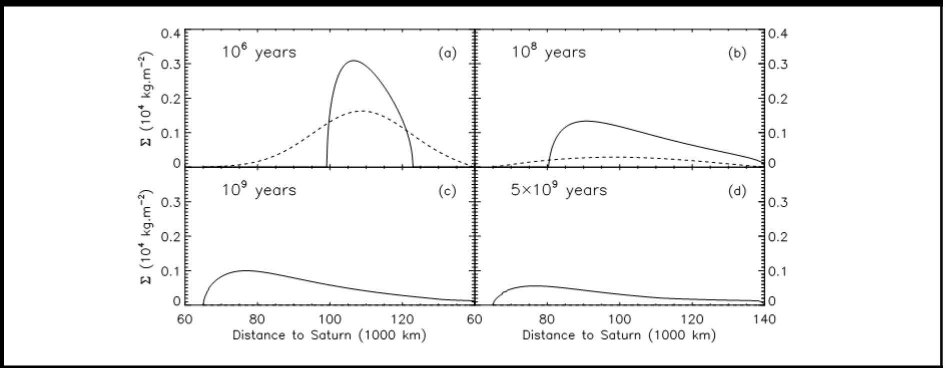


Coupling of 4 processes

- Ring viscous spreading
- Accretion beyond the roche limit
- Resonant interactions with rings
- Tidal interaction with Saturn

Moon formation

Spreading of Saturn's rings :
- a process still active
- Ring's spreading is enhanced due to grav. instabilit

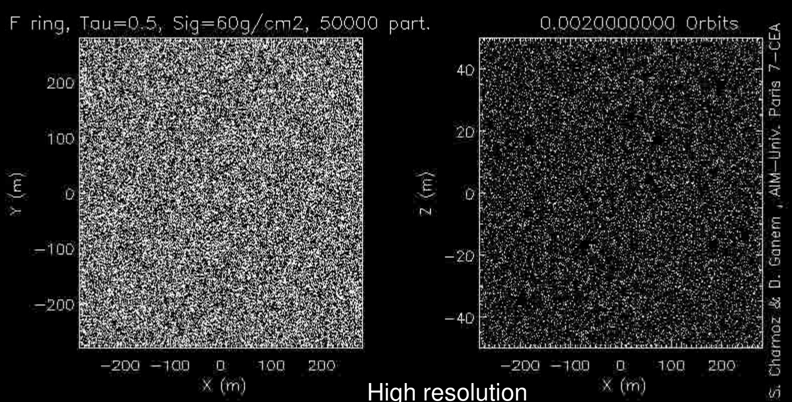


Salmon et al., 2010

Accretion at the ring's edge : gravitational instability

When material crosses the Roche Limit, (~140000 km) it may become become gravitationally unstable

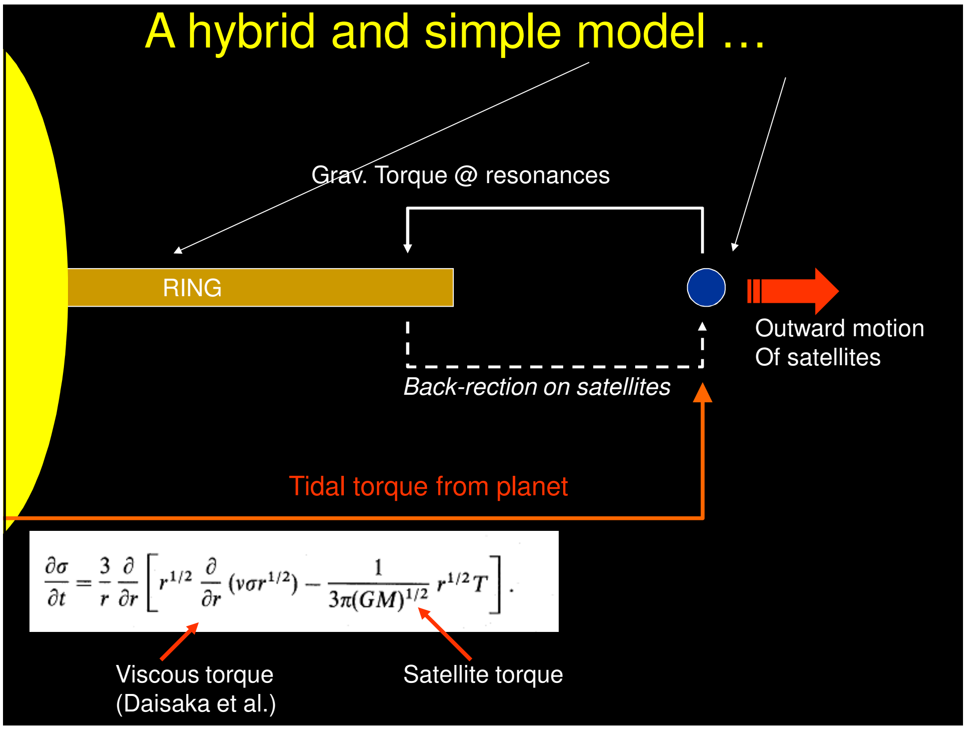
Example : « patch » simulation of a disk > Roche Limit

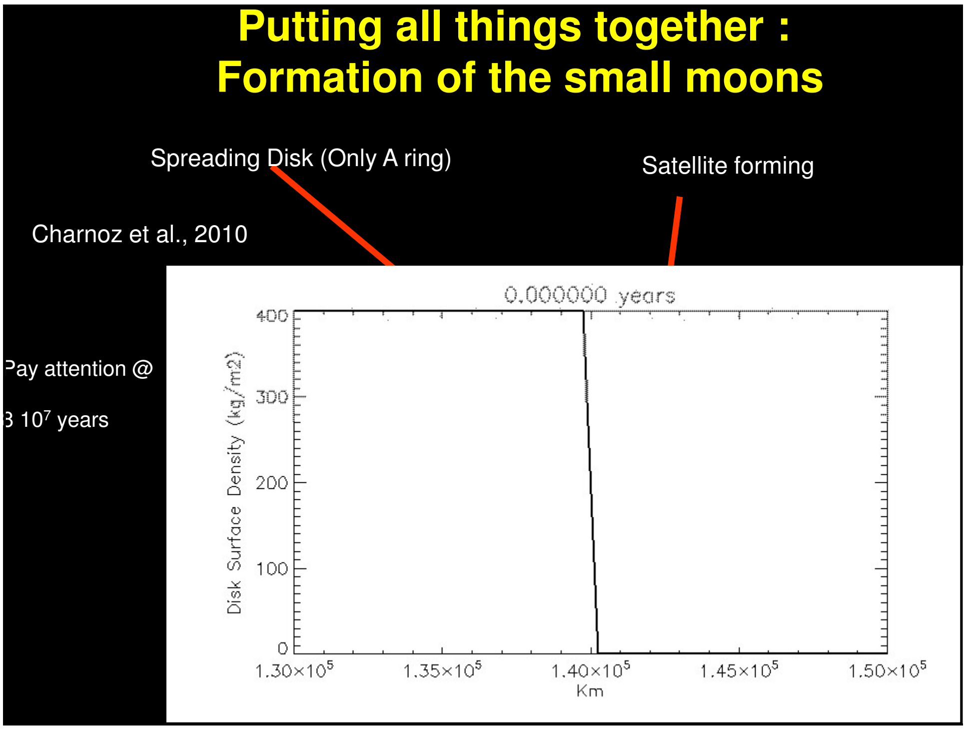


High resolution

Formation of aggregates when Q<1

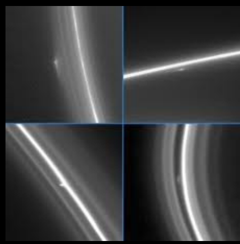
Simulation :
Charnoz / Decriem


A hybrid and simple model …
Grav. Torque @ resonances
RING
Outward motion
Of satellites
Back-rection on satellites
Tidal torque from planet
$\frac{\partial \sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}(\nu\sigma r^{1/2}) - \frac{1}{3\pi(GM)^{1/2}} r^{1/2} T \right].$
Viscous torque
(Daisaka et al.)
Satellite torque

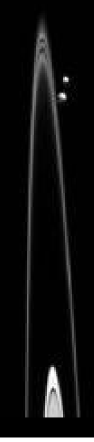

Putting all things together :
Formation of the small moons
Spreading Disk (Only A ring)
Satellite forming
Charnoz et al., 2010
Pay attention @
3 10^7 years
0.000000 years
Disk Surface Density (kg/m2)
400
300
200
100
0
1.30×10⁵
1.35×10⁵
1.40×10⁵
1.45×10⁵
1.50×10⁵
Km

Explains :

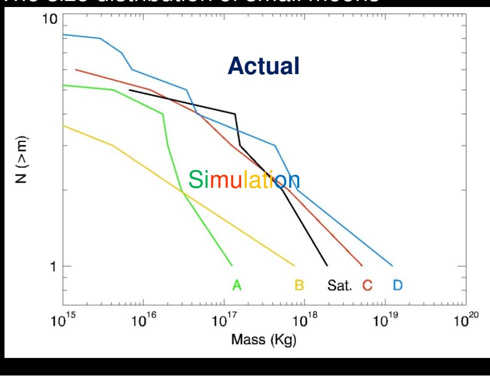
The origin of the F ring



The confinement of the A ring by Janus

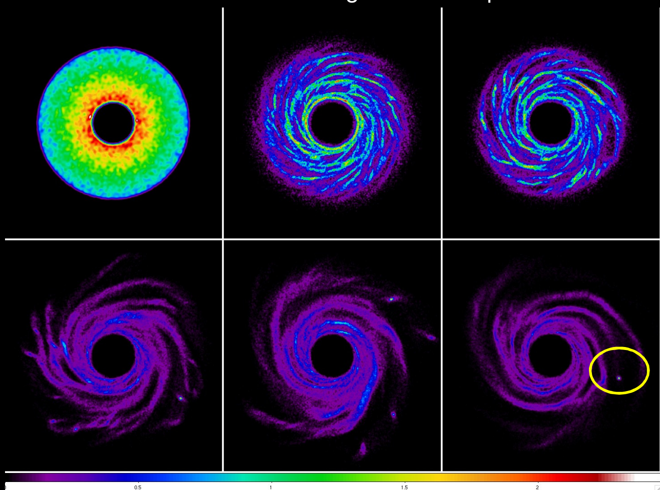


The size distribution of small moons



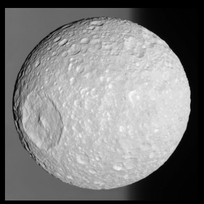
But ..not such a new process !!
Same as Earth's moon formation … but with a lighter disk

Protolunar disk = a ring around the proto-earth

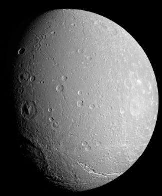


Our Moon
Forms from
The protolunar
disk

Mid-sized icy satellites : strange small worlds

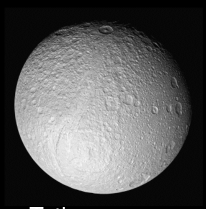


Mimas

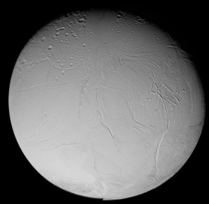


Dione

Rhea



Tethys

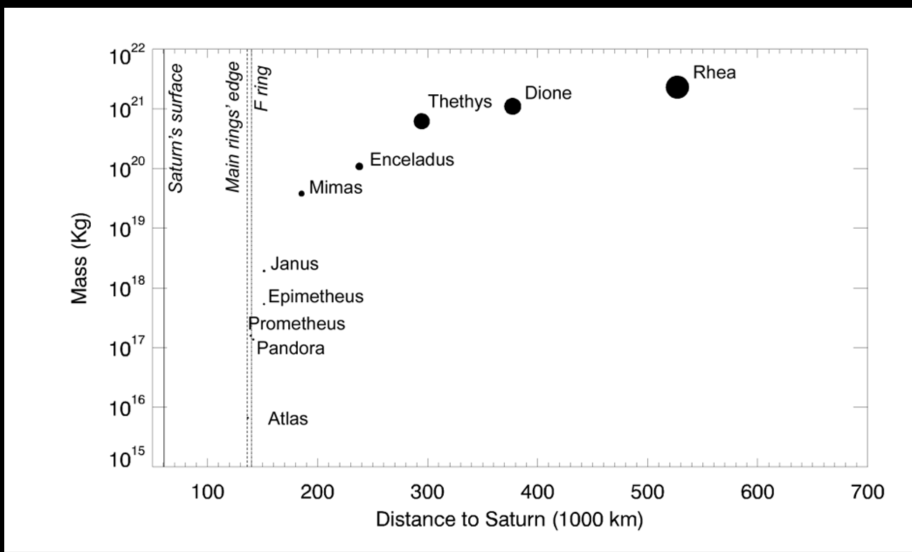


Enceladus

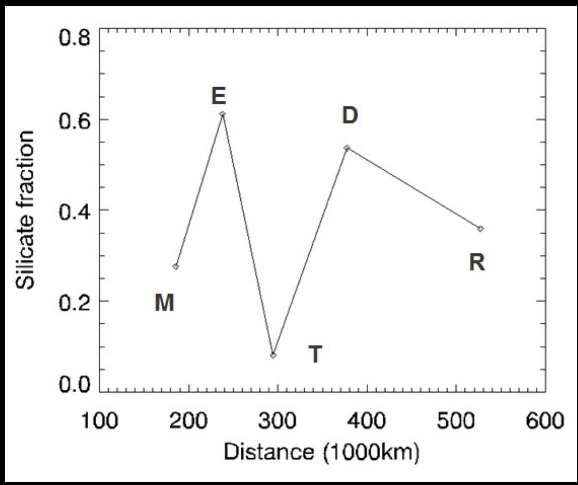
Cf.
Paul Schenk's talk

Nico Schmedemann 's talk

Dificulties to explain the today orbital architecture



Varying abundances of silicates



2 populations of impactors ?

<u>Type I : Heliocentric (R,I)</u> population (comets ?) with large impactors

<u>Type 2 : planetocentric (M,E,T)</u> population with mid-sized impactors At least for Mimas, Enceladus, Tethys, Dione

Smith et al., 1981, 1982, Chapman & McKinnon (1986), Lissauer et al., (1988) Dones et al. (2009)

Does surface relaxation may have played a role for Dione, Mimas, and Tethys ?

Is it an effect of saturation ?

⇒Unclear (cf. Kirchoff & Schenk 2010, Chapman & McKinnon (1986),)

A new perspective : Origin of moons linked with rings' origin

Is it possible to form all inner moons from the rings only ?

What are the consequences ?

Key ingredients of this work

- Massive initial Saturn's rings (Salmon, 2010, Canup 2010,OK)
- The ring's parent body was an *almost* perfectly differentiated object
- Saturns' Q dissipation factor (high ? Low ?)

NO HYPOTHESIS on :

- the mecanism that breaks the parent body

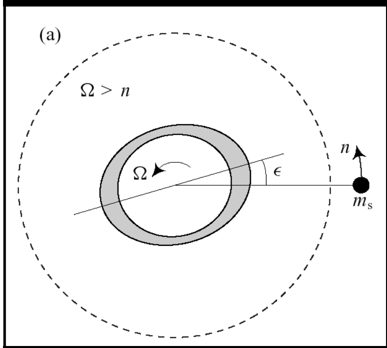
(tidal destruction ok , impact ok (if possible), …)

- the date T of the event (2 Gyr < T < 4.5 Gyr)

(Saturn formation Ok, LHB OK, ….)

Saturn's Q : the Tidal torque

High Q => Weak tides | **Small Q => Strong tides**



$$\frac{da}{dt} \propto \frac{k_2}{Q}$$

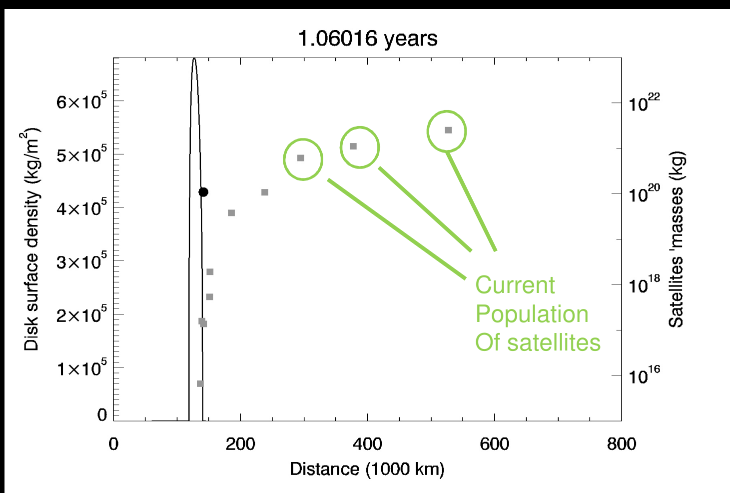
Two cases are considered

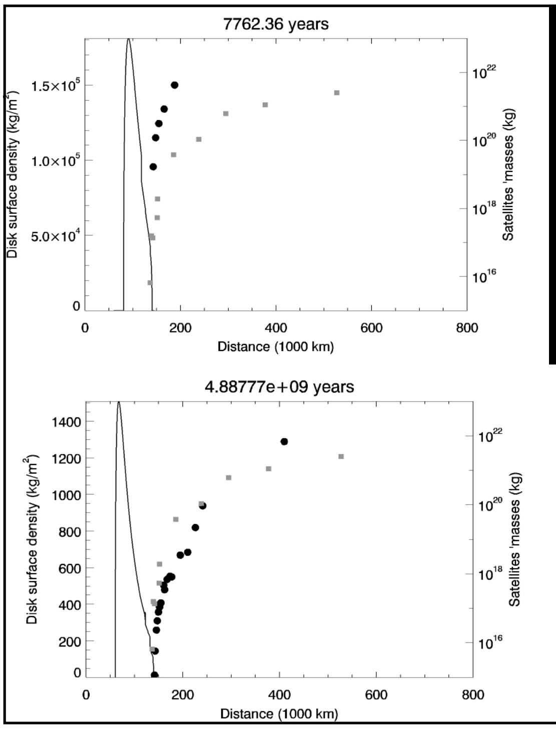
1) Q=18000
(standard value, 4 assumptions)
(Goldreich & Soter 1966, Gavrilov & Zharkov 1977)

2) Q=1600
(Layne et al., 2011, Measure, Paper submitted)

SIMULATING THE RING EARLY EVOLUTION

A ring with 4 Rhea Mass (1000x Saturn rings) & Q_{saturn}=18000





Q=18000

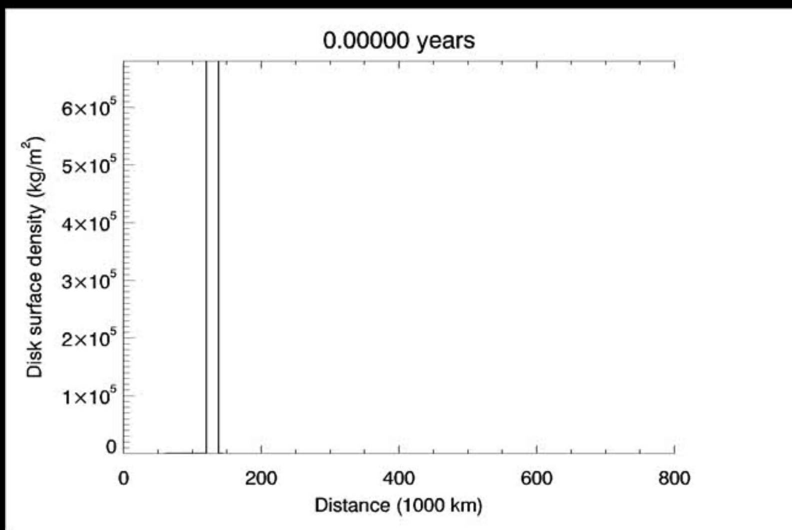
No dissipation in satellites

Result is encouraging but

poor agreement with Today's population

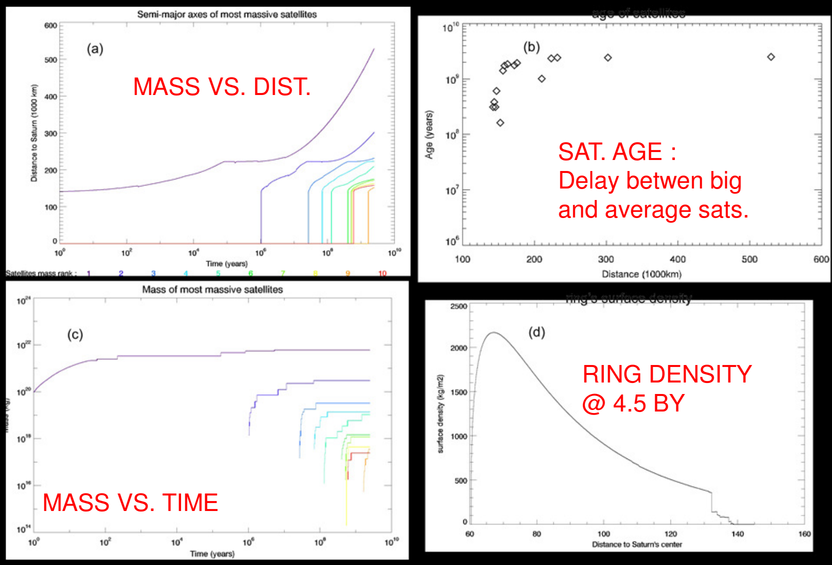
Inclusion of strong Saturn's dissipation : Q=1600 + satellite dissipation

Ring's density



Moons' masses

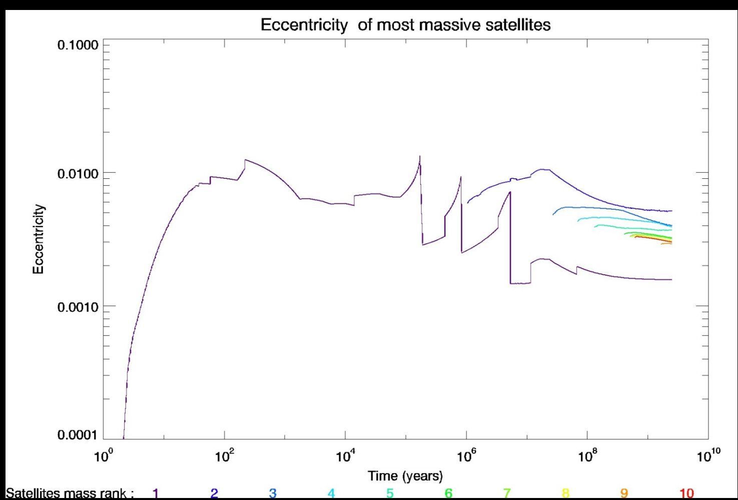
Interesting consequences

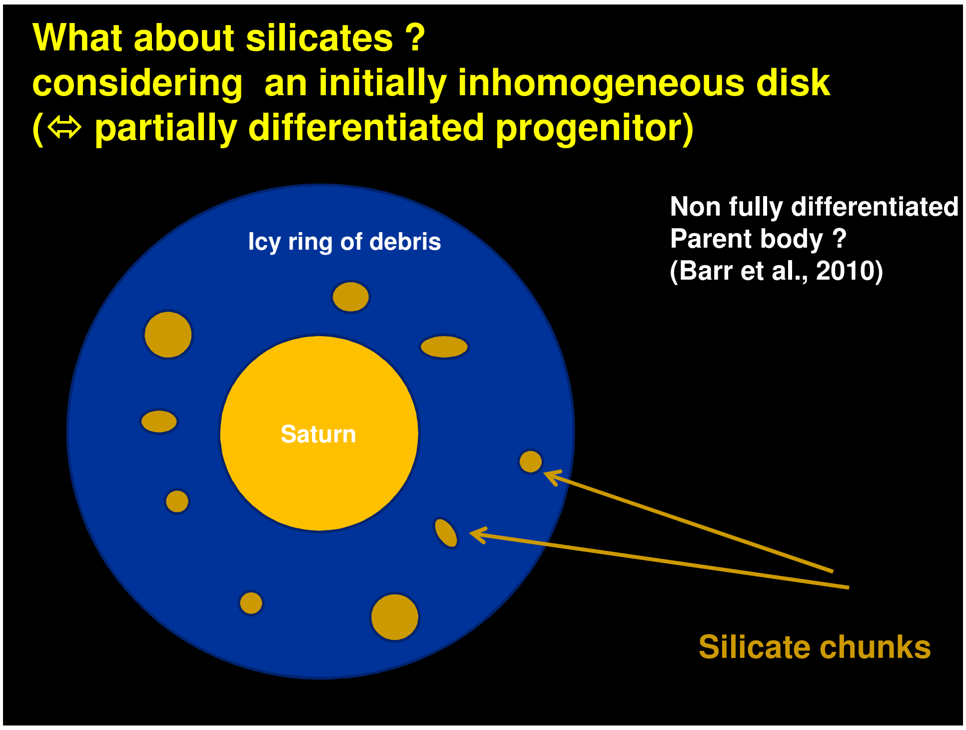


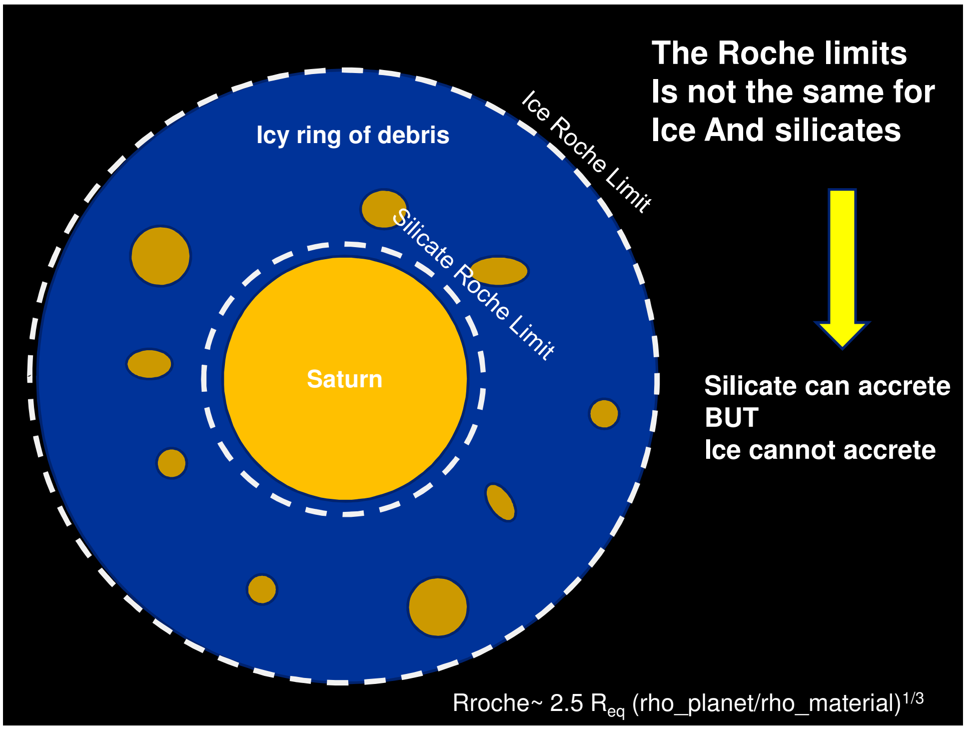
Moons have different ages

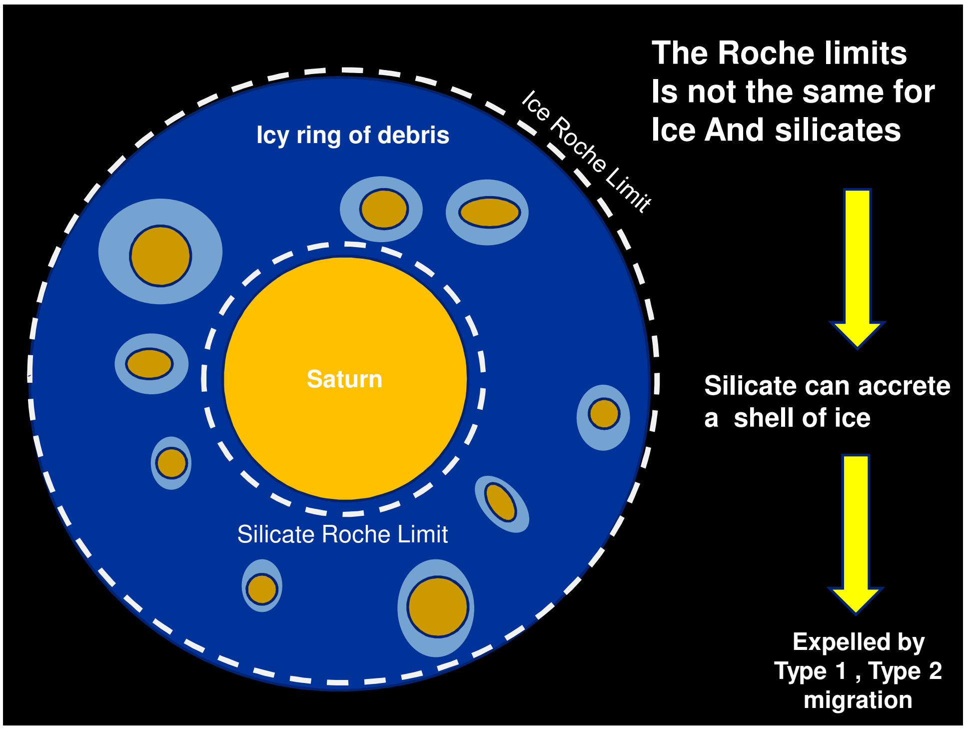
Accretion occur in low Impact velocities (<1km/s) of same size

Eccentricity of satellites vs. Time => Early geological evolution



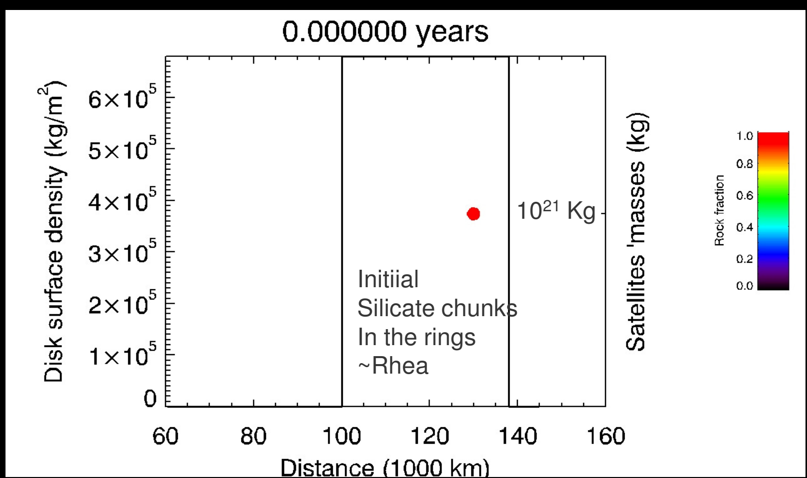

What about silicates ?
considering an initially inhomogeneous disk
(⇔ partially differentiated progenitor)
Non fully differentiated
Parent body ?
(Barr et al., 2010)
Icy ring of debris
Saturn
Silicate chunks

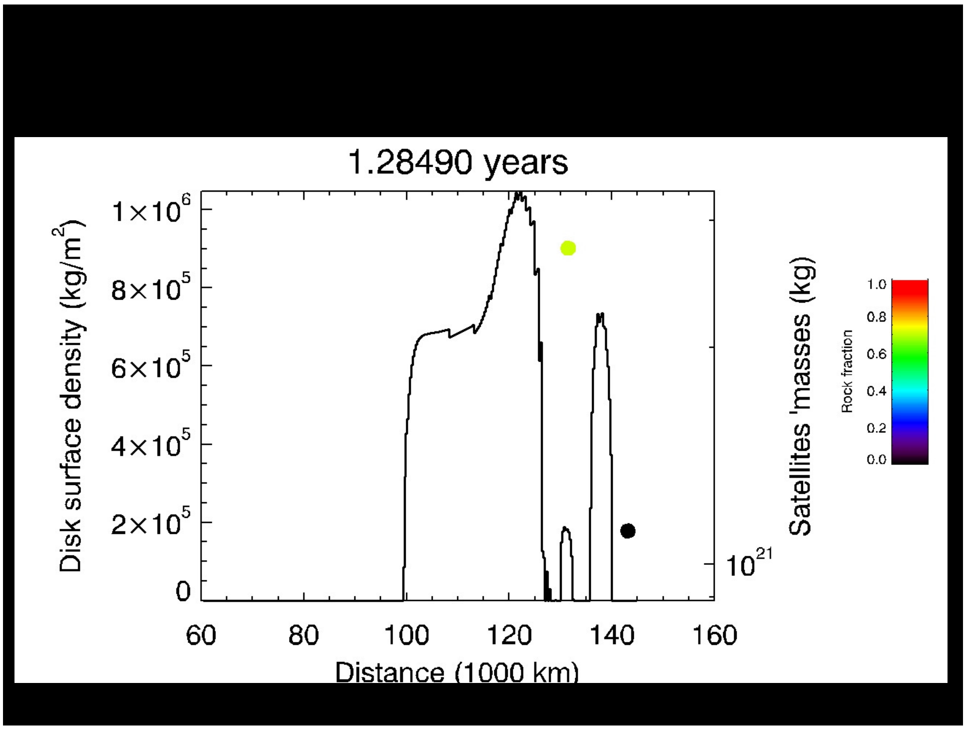

The Roche limits
Is not the same for
Ice And silicates
Icy ring of debris
Ice Roche Limit
Silicate Roche Limit
Saturn
Silicate can accrete
BUT
Ice cannot accrete
Rroche~ 2.5 R_{eq} (rho_planet/rho_material)$^{1/3}$

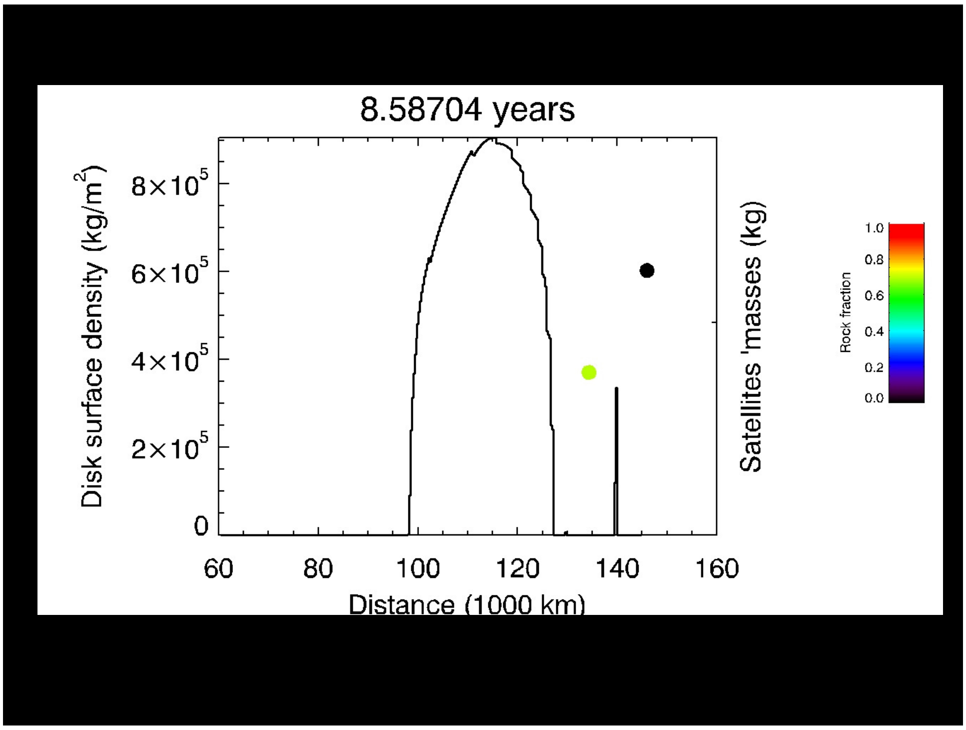


SIMULATION : T1-T2 Migration + Accretion

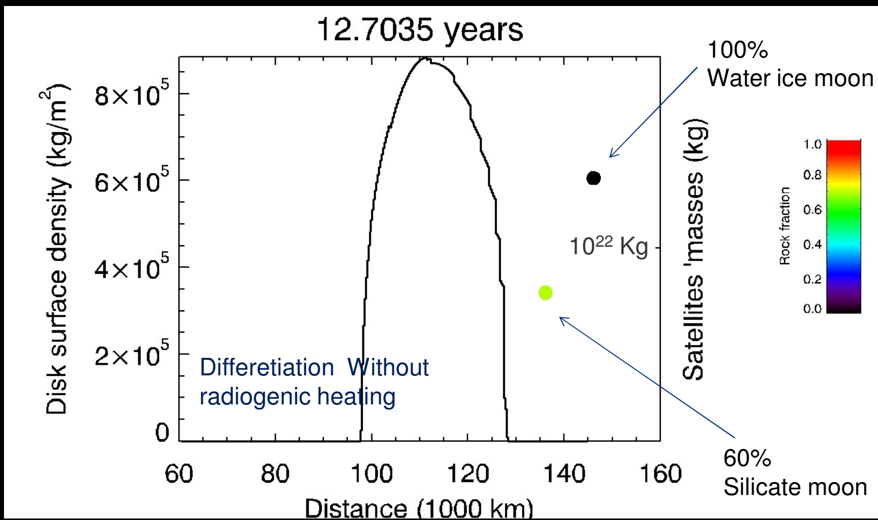
Evolution of siliicate chunks embedded the initial rings




1.28490 years
Disk surface density (kg/m²)
1×10⁶
8×10⁵
6×10⁵
4×10⁵
2×10⁵
0
60
80
100
120
140
160
Distance (1000 km)
10²¹
Satellites 'masses (kg)
Rock fraction
1.0
0.8
0.6
0.4
0.2
0.0

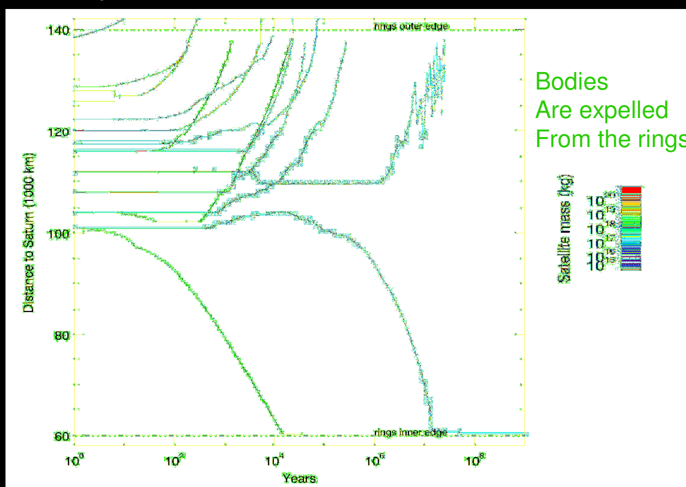

8.58704 years
Disk surface density (kg/m²)
8×10⁵
6×10⁵
4×10⁵
2×10⁵
0
60
80
100
120
140
160
Distance (1000 km)
Satellites 'masses (kg)
Rock fraction
1.0
0.8
0.6
0.4
0.2
0.0

We end with a 50% rock fraction satellite
+ a 0% rock fraction satellite



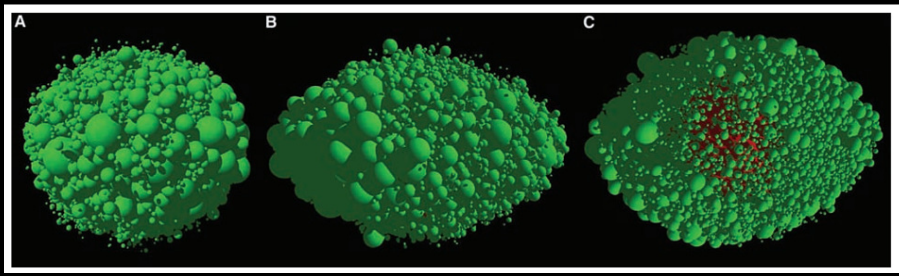
Progressively all silicates are expelled from the rings
due to Type I and Type II migration

Big objects are expelled first
Small objetcs are expelled later

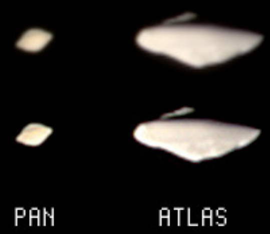


Consistent with :

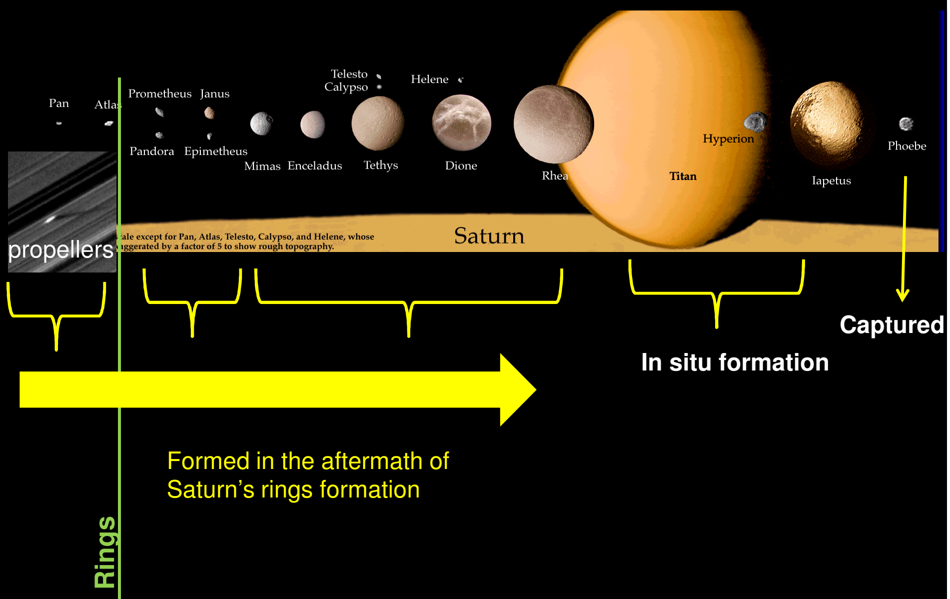
Porco et al., 2007 : Shape of small moons



Charnoz et al., 2007 : equatorial ridges



SATURN's MOONS
Diversity of formation processses



FUTURE

Explore all planets

Terrestrial planets

Gian planets

Extra-Solar planets

Understand rings

Related works @ ESLAB

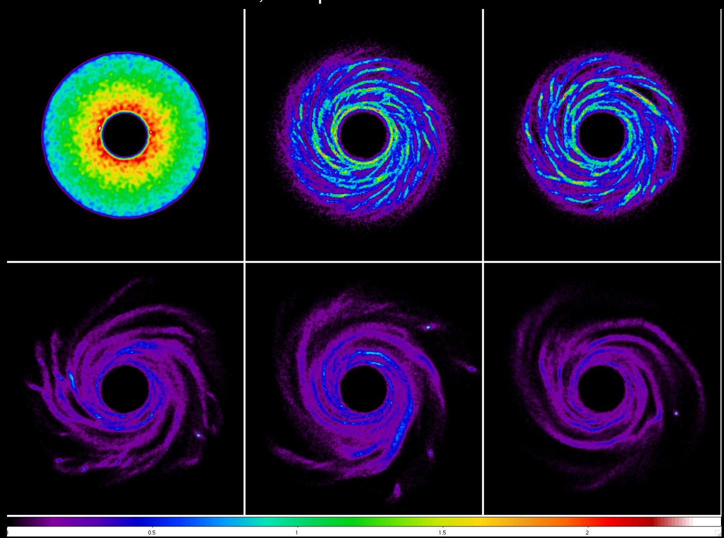
1. Aurelien CRIDA (MONDAY): analytical description , consequences for Uranus, Neptune, Earth
2. François REMU (MONDAY): interior of Saturn, possibility of a strong dissipation
3. Pascal ROSENBLATT (TUESDAY) : formation of Phobos and Deimos from a viscously spreading circum-martian disk
4. Radwan TAJEDDINE (WEDNESDAY) : constraining Mimas interior for possible irregular core.
5. Kevin DEGIORGIO (WEDNESDAY) :constrains on craters properties of Saturn's MSM

Etc.

THE END

Conclusion : Same process as Earth's Moon formation

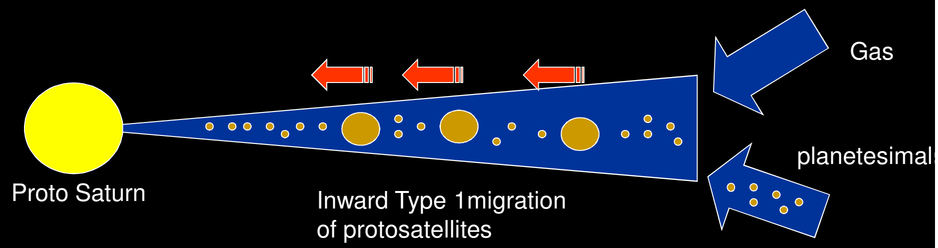
500, 000 particles. Galactic code

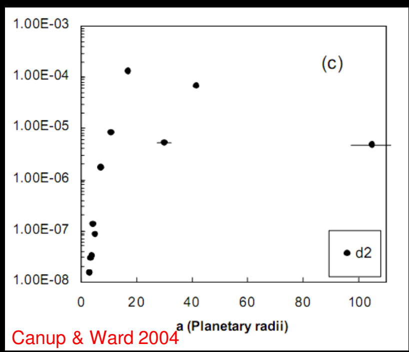


36

Bourneaud , Charnoz , 2011

In moons formation models, all satellites migrate toward the planet





Work of
Canup & Ward
Mosqueira & Estrada

The tidal effects and the estimation of Q

Estimation of lower bound of Q for the giant planets by Goldreich and Soter (1966)

$Q_{Jupiter} \geq 1.0\ 10^5$ (Io)
$Q_{Saturn} \geq 6.0\ 10^4$ (Mimas)
$Q_{Uranus} \geq 7.2\ 10^4$ (Miranda)

Let's remind that:
$Q_{Mars} \approx 80$
$Q_{Earth} \approx 260$
$Q_{Io} \approx 20$

Values further improved by Gavrilov and Zharkov (1977) (Same k2/Q, but improved k2)

$Q_{Jupiter} \geq 2.5\ 10^4$ (Io)
$Q_{Saturn} \geq 1.4\ 10^4$ (Mimas)
$Q_{Uranus} \geq 5.0\ 10^3$ (Miranda)

These values are still good references!

Goldreich 1966 's arguments for Q

Gives a lower bound of Q assuming

- All satellites formed simultaneously
- Mimas start at synchronous orbit (@117 000 km) and end at its current location
- Mimas appeared 4.5 Gyr ago
- Mimas appeared with its FINAL mass

In our model we get

- ~~All satellites formed simultaneously :~~
  - **No , ~1Gy delay between Mimas & Rhea**
- ~~Mimas start at synchronous orbit (@117 000 km) and end at its current location~~
- **No, ~ formed ~140000 km**
- ~~Mimas appeared 4.5 Gyr ago~~
- **No < 3 Gyr ago**
- ~~Mimas appeared with its FINAL mass~~
- **No : slow accretion**

III Application to the Jovian and Saturnian system

Collaboration with: Ö.Karatekin, J.Desmars, S.Charnoz, J.E.Arlot, N.Emelianov, C.Le Poncin-Lafitte,S.Mathis,F.Remus, G. Tobie, J.-P.Zahn

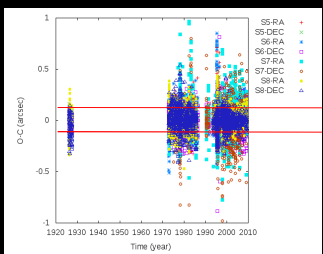
The application for Saturn is slightly different than for Jupiter:

1- the ring is exerting a torque on the satellites (Mimas 2:1 resonance!)

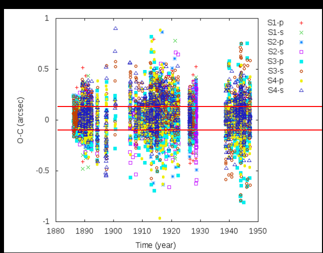
2- the observations are less accurate

3- dissipation in the satellites will be harder to catch (smaller radii)

III Application to the Jovian and Saturnian system



0.1 arcsec ~ 600 km



→Residuals after fitting the initial state vectors of all the eight main Saturn moons, the ratio k_2/Q inside Saturn and a constant drift da/dt.

Observation subset:	ν_s	σ_s	ν_p	σ_p	N_s, N_p
All Observations:					
S1	0.0140	0.1027	0.0131	0.1152	1285, 1298
S2	-0.0032	0.0988	0.0048	0.1069	2640, 2643
S3	0.0157	0.1130	-0.0003	0.1152	4702, 4700
S4	0.0150	0.1045	0.0023	0.1096	3775, 3776
S5	0.0113	0.1088	0.0030	0.1151	4471, 4489
S6	0.0238	0.0937	-0.0049	0.1084	2842, 2836
S7	0.0017	0.3275	0.1068	0.4838	138, 113
S8	0.0179	0.0766	0.0076	0.1246	1098, 1101

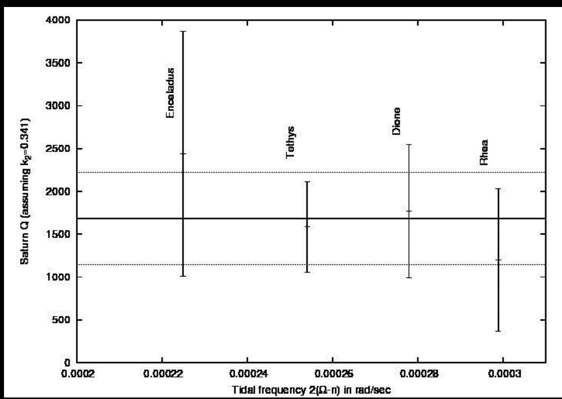
Observation subset:	$\nu_\alpha \cos(\delta)$	$\sigma_{\alpha \cos(\delta)}$	ν_δ	σ_δ	N_α, N_δ
All observations					
S1	-0.0057	0.0952	-0.0108	0.0725	371, 371
S2	0.0019	0.1040	0.0028	0.1101	822, 822
S3	-0.0199	0.1267	0.0122	0.1067	1972, 1972
S4	0.0020	0.1066	0.0113	0.1067	2271, 2271
S5	0.0047	0.0899	-0.0023	0.0863	2977, 2977
S6	0.0121	0.1060	-0.0171	0.1070	3271, 3271
S7	0.1098	0.2984	0.0036	0.2166	973, 973
S8	0.0140	0.1143	-0.0052	0.1155	2008, 2008

Lainey et al. (submitted)

$k_2/Q = (2.3 \pm 0.7) \times 10^{-4}$;
da/dt$= -(15.7 \pm 4.4) \times 10^{-15}$ au/day.

III Application to the Jovian and Saturnian system

In a second step we release as free parameters one k_2/Q ratio per tide raising satellite…

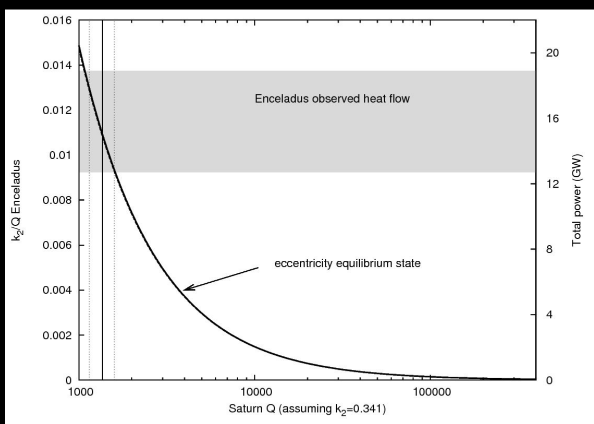


Tidal dissipation seems to be a smooth function of tidal frequency. Hence, such strong dissipation cannot come from the atmosphere.
→Strong tidal dissipation may arise in the icy core.

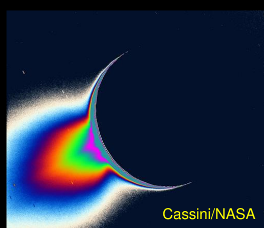
Since the Jovian core may be much smaller than Saturn's, this may explain the order of magnitude in the tidal ratio obtained.

III Application to the Jovian and Saturnian system

Meyer & Wisdom (2007) showed that tidal heating equilibrium is not possible for Enceladus (using Q≥18,000 from Sinclair 1983).



But our present result suggests that it is possible (Q=1682 +/-540)



Low impact velocities of impactors ??

See Nico's talk (@PSG, Neukum's team)

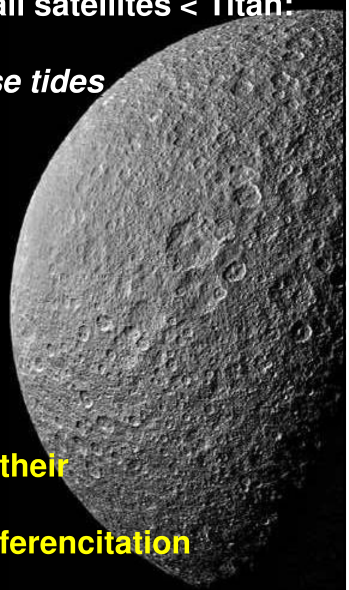
CONCLUSION

A single mechanism may have formed all satellites < Titan:

Ring viscous spreading + Saturn intense tides

Mimas age much younger than Rhea

Moons are « pre-differenciated » when they forme

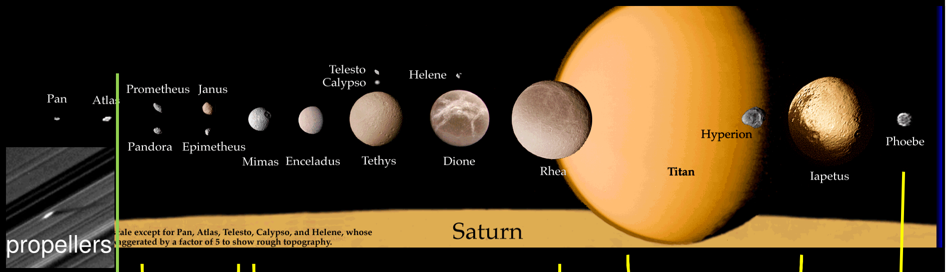


Solves

- cratering age Rhea Vs. Iapetus

* Implantation of Saturn's icy moons at their Current location (with q=1600)
* Do not nead radiogenic heating for differencitation

Diversity of formation process ?
In situ formation may not be the unique process



???

Problem:
Dynamic age << Solar System
+
orbits

Problem:
Varying abundance of silicates
+
orbits

In situ formation

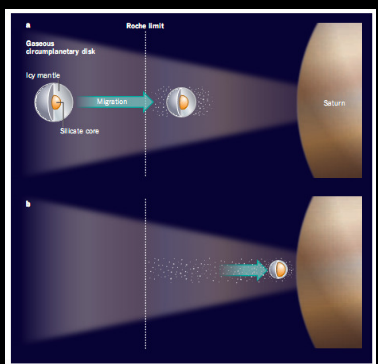
Captured

Rings

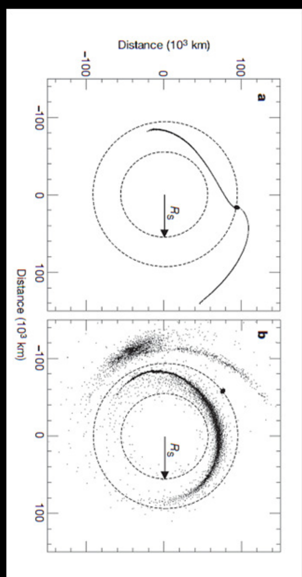
Tidal peeling of the outer shell of a differentiated satellite

A Titan-sized parents bodies spiral inwards to Saturn(type I migration)

Tidally stripping of the differentiated satellite :
=> icy debris disk



Crida & Charnoz 2010 (news & views)



Canup, 2010

Rhea Vs. Iapetus craters … :also very mysterious

Saturn's gravitational focusing :

Rhea has ~ 100 times less crater than expected if impacted by the same heliocentric population as Iapetus

Smith et al. (1981) ,Zahnle et al. (2003), Dones et al.

Indeed :

Focus $\propto (1+V_{esc}(r)^2 / V_\infty^2) = (1+2GM/(RV_\infty^2))$

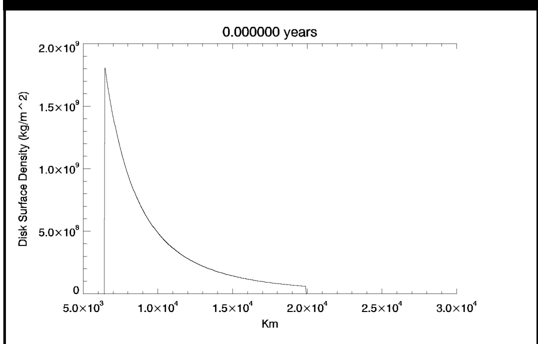
$\Rightarrow$ **Crater density ~ $\propto$ 1/R close to the planet**

$\Rightarrow$ **The crater density on Rhea should be >> Iapetus**

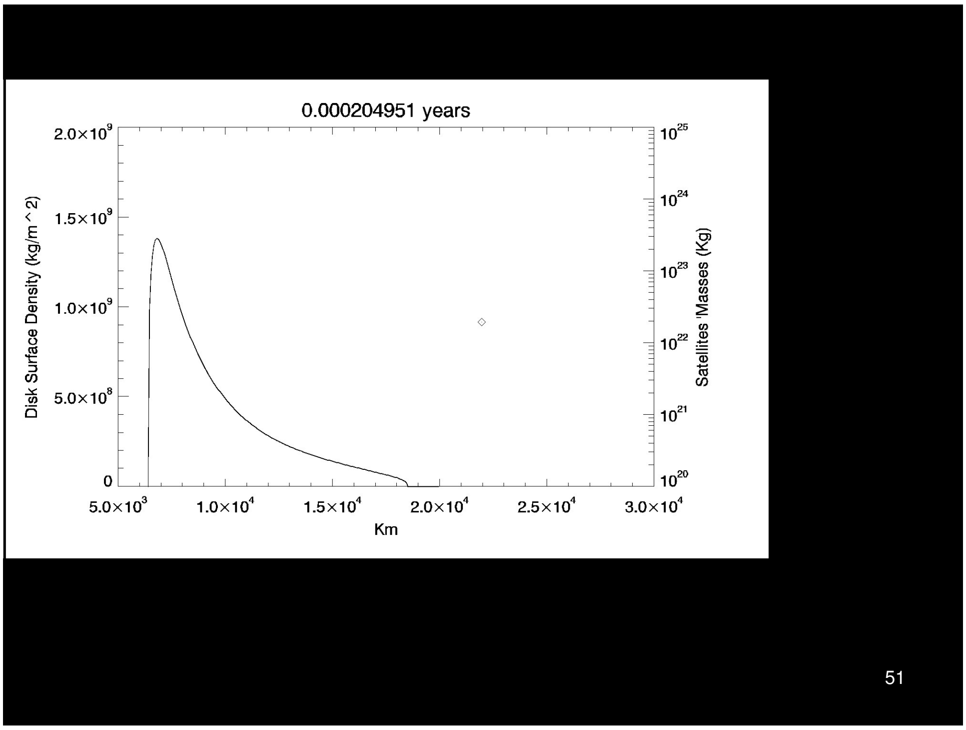
Travaux déjà faits / Outils à notre disposition

1) Modèle hydro de disque + accrétion de satellites pour les sat. De Saturne

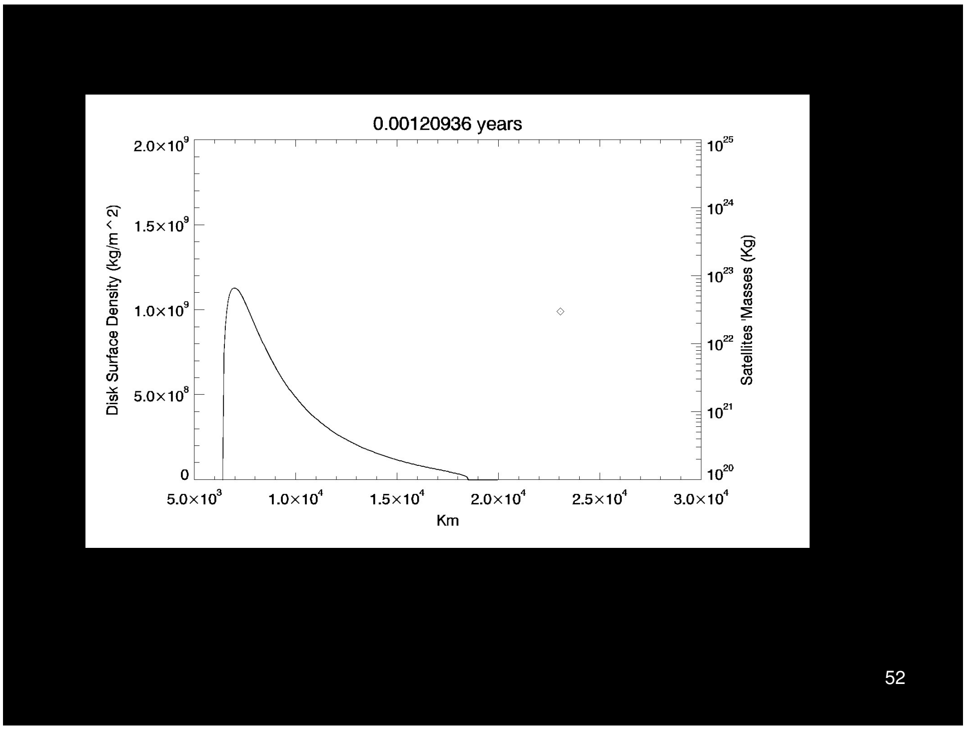
$\Rightarrow$ Charnoz et al., Nature 2010



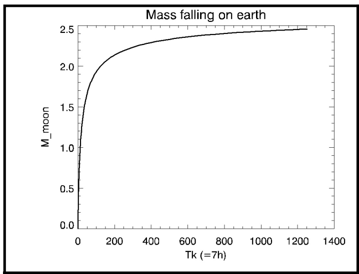
50



0.000204951 years
Disk Surface Density (kg/m^2)
Satellites 'Masses (Kg)
Km
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
2.5×10^4
3.0×10^4
10^25
10^24
10^23
10^22
10^21
10^20
51



0.00120936 years
Disk Surface Density (kg/m^2)
Satellites 'Masses (Kg)
Km
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
2.5×10^4
3.0×10^4
10^25
10^24
10^23
10^22
10^21
10^20
52

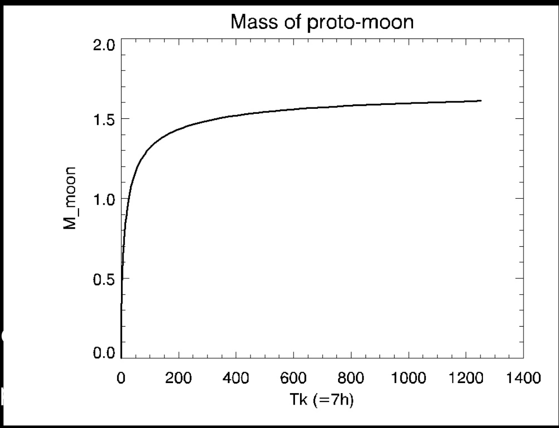


OK

Objectif :

Rajouter la diffusion
Des espèces isotopiqu

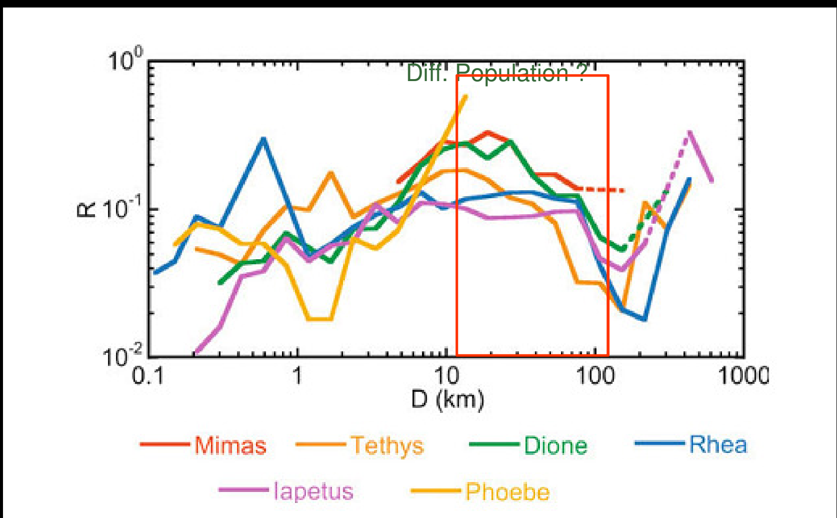
Et l'évolution de la tem
Du disque
=> Modifie la viscosité



53

Craters records of icy moons

« R-plot »: relative to a D^{-3} distribution

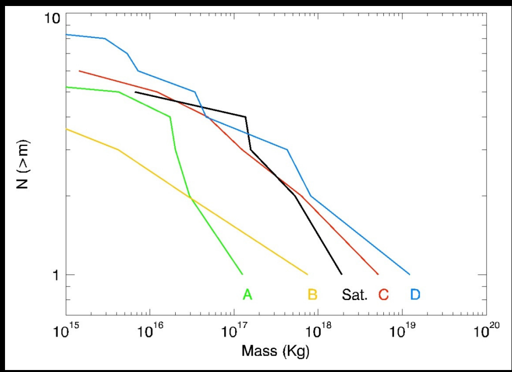


[Mimas, Tethys Dione] Vs. [Rhea, Iapetus]

Kirchoff & Chenk (2010) .

Compatible with

Mass distribution of small moons



+ **Existence of Saturn's F ring**

+ **Confinment of the ring's outer edge**

What happened on Rhea or Iapetus ?

Zahnle et al. 2003). The Voyager results seem to imply one or more of the following: (1) Iapetus and Rhea were cratered by different populations of impactors; (2) the most heavily cratered terrains on all the moons are saturated; (3) more crater relaxation has taken place on Rhea than on Iapetus; or (4) Rhea's surface is, on average, considerably younger than that of Iapetus (Lissauer et al. 1988).

Dones et al., 2010

Maybe a population of irregular moons have impacted Rhea ?
(Nesvorny et al., 2007)

?

Interesting properties of heterogeneous accretion in rings: Exploring some basic physics

Consensus that Rings may have formed from the destruction of a satellite or comets (Harris , 2984)

- Canup 2010 : tidal stripping of a Titan-sized differentiated satellites + elimination of the core
- Charnoz et al., 2009 : impact on a differentiated satellite during the LHB
- Dones 1991 : Tidal stripping of comets

In all cases, you end with a mix between ice and silicates
(in the Canup case, maybe most of silicates are already eliminated)

The tidal efficacity inside Saturn is poorly constrained :

It is given by K2/Q (K2~0.341 for Saturn)

When Q is high Dissipation is weak => slow orbital expansion

When Q is low, dissipation is strong => fast orbital expansion

Canonic value : Q=18000 (from Goldreich & Soter 1966)

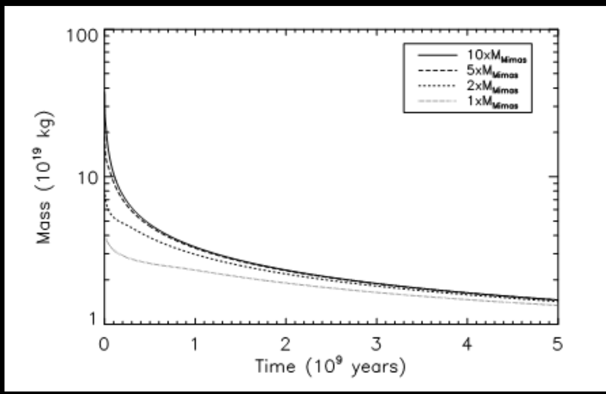
Assuming that Mimas must be at its current location after 4.5 Gy of Orbital expansion from the Synchronous orbit

New measurements from Astrometric observations : Q=1600 !! (unpublished) .. May reveal the presence of a core

BOTH VALUES WILL BE CONSIDERED

MAIN CONSEQUENCE 2 :

Final mass of the ring ~independant of the initial mass



Viscous spreading timescales
$\Delta T \propto Mi^{1/2}$

Asymptotic ring Mass
1,02 10^{19} Kg ~ (1/3 Mimas (Salmon et al., 2010)

Coherent with Robbins et al. (2010)

Is it possible to start With massive rings ?

Does an initial massive ring could be compatible with the current ring system ?

Ring's viscous spreading : Revisiting old results

Long term spreading of rings using « realistic » viscosity

Salmon, J., Charnoz S., Crida A., Icarus , June 2010

$$\nu = \nu_{\mathrm{trans}} + \nu_{\mathrm{coll}} + \nu_{\mathrm{grav}}, \qquad (7)$$

with

$$\nu_{\mathrm{trans}} = \begin{cases} \frac{\sigma_r^2}{2\Omega}\left(\frac{0.46\tau}{1+\tau^2}\right) & \text{if } Q > 2, \\ \frac{1}{2}26 r_{\mathrm{h}}^{*5}\frac{G^2\Sigma^2}{\Omega^3} & \text{if } Q < 2, \end{cases} \qquad (8)$$

$$\nu_{\mathrm{coll}} = r_{\mathrm{p}}^2\Omega\tau \quad \forall\, Q, \qquad (9)$$

$$\nu_{\mathrm{grav}} = \begin{cases} 0 & \text{if } Q > 2, \\ \nu_{\mathrm{trans}} & \text{if } Q < 2, \end{cases} \qquad (10)$$

Daisaka. (2001)

Viscosity is HIGH when Q < 2 (self-gravitating)

Viscosity is LOW when Q>2 (non self-gravitating)

Toomre's parameter

$$Q = \frac{\Omega\sigma_r}{3.36 G\Sigma},$$

Constant viscosity Vs. Realistic viscosity

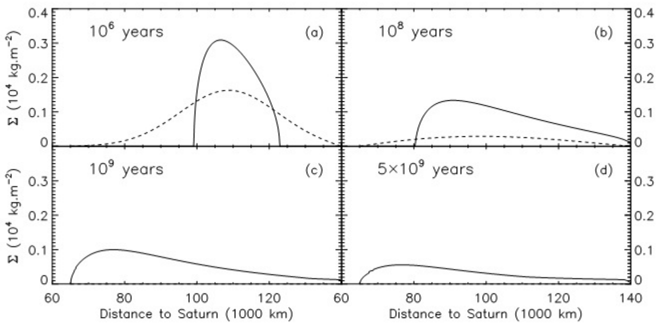


Fig. 4. Disk surface density at different evolution times with variable (solid line) and constant (dashed line) viscosities. **(a)** At 1Myrs of evolution. **(b)** At 100 Myrs of evolution. **(c)** At 1 Gyrs of evolution. **(d)** At 5 Gyrs of evolution. The disk with constant viscosity is emptied in ~ 10^9 years, while the disk with variable viscosity remains massive over 5 Gyrs with a density peak inward and lower densities outward.

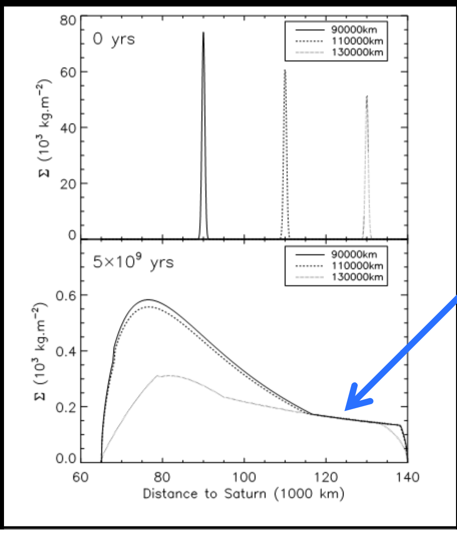
Spreading Timescale : $\Delta R \propto t^{1/4}$

Salmon et al., 2010

(rather than $\Delta R \propto t^{1/2}$ for cst. Viscosity)

Independance from initial conditions

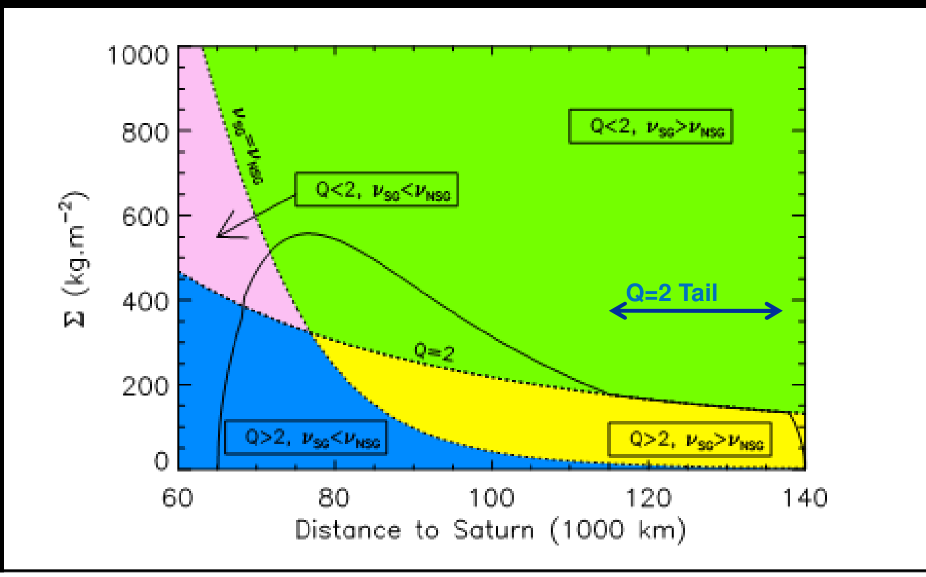
Formation of a « density plateau » at large Radius



Q ~2

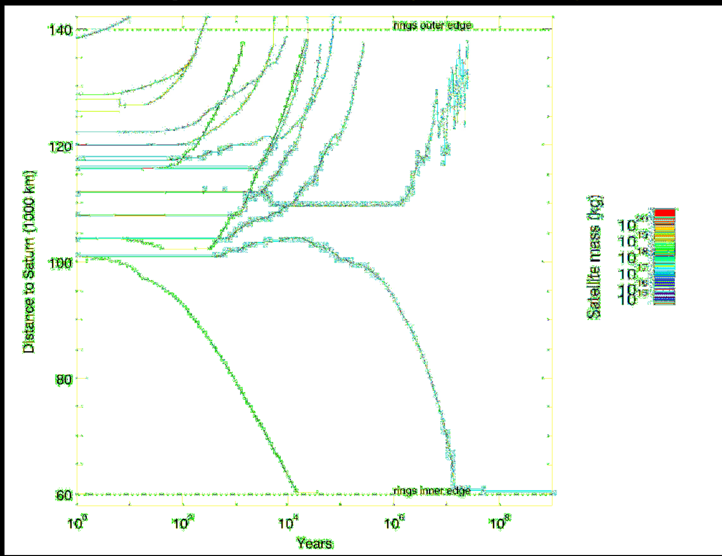
MAIN CONSEQUENCE 1 :

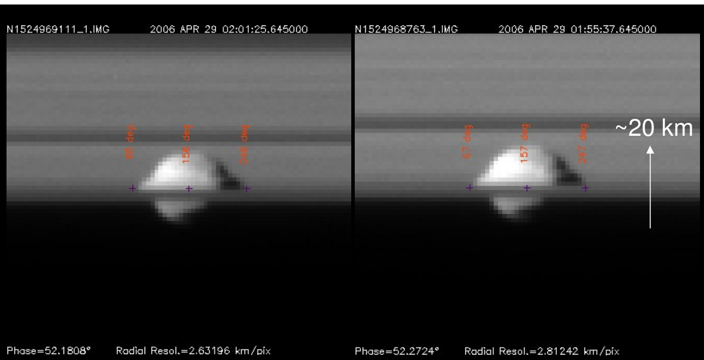
Formation of a Q=2 plateauat large radii (⇔ A Ring ?)



Migration of silicates chunks:
Multiple tests with multiple disks : Always end in ejection

Those suffering
Type 1 migration
Are longer to be
ejected



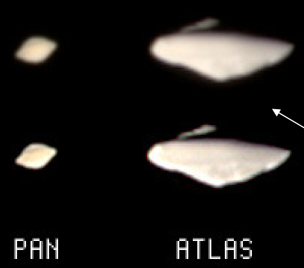


ISS-NAC

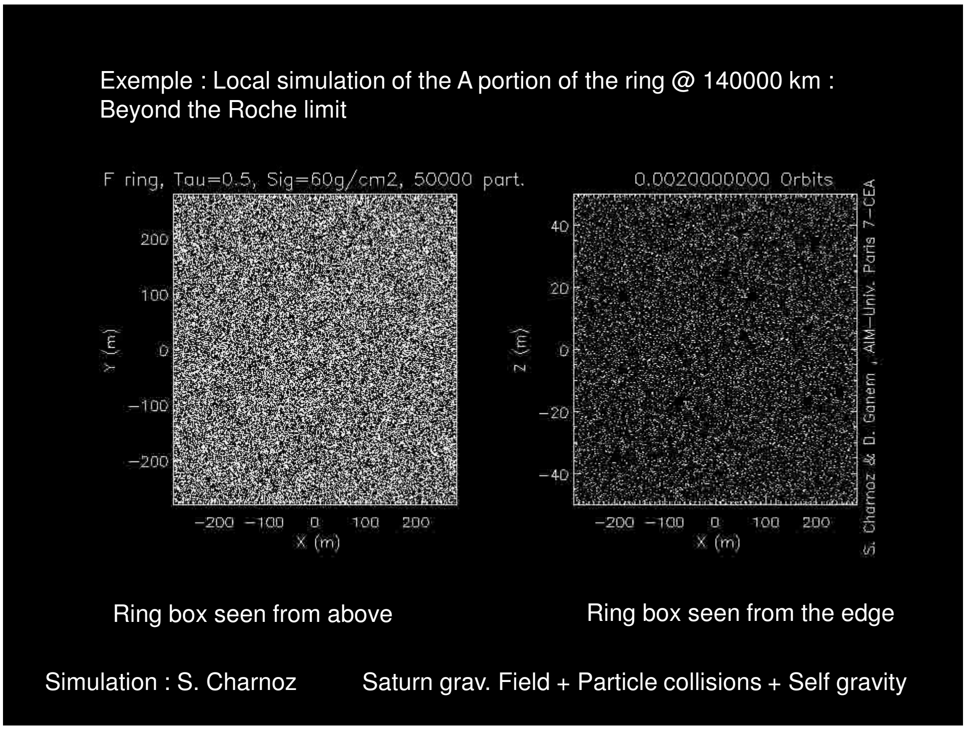
Pan

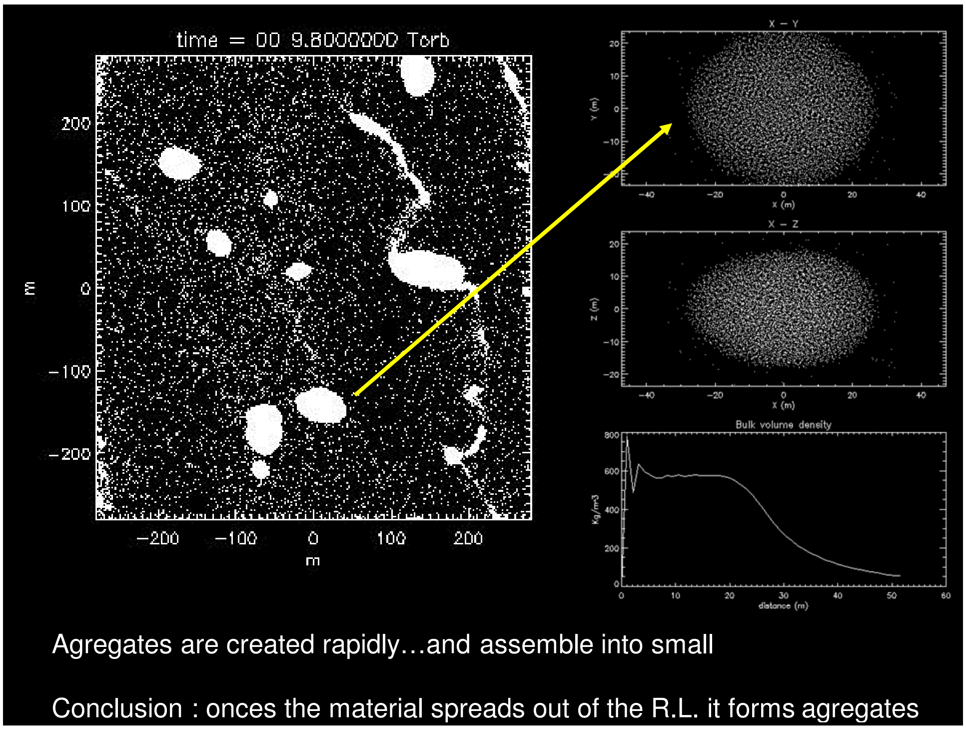
Bulge seems
to encircle
the body

Extension ~
±15°



ATLAS

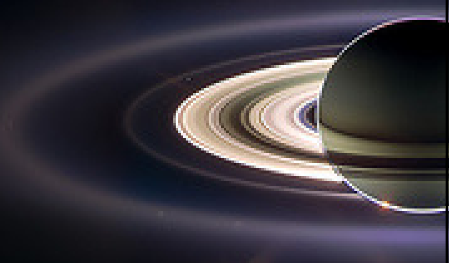

Exemple : Local simulation of the A portion of the ring @ 140000 km :
Beyond the Roche limit
F ring, Tau=0.5, Sig=60g/cm2, 50000 part.
0.0020000000 Orbits
Y (m)
Z (m)
X (m)
S. Charnoz & D. Ganem , AIM–Univ. Paris 7–CEA
Ring box seen from above
Ring box seen from the edge
Simulation : S. Charnoz
Saturn grav. Field + Particle collisions + Self gravity


time = 00 9.8000000 Torb
m
X – Y
X – Z
Bulk volume density
Agregates are created rapidly…and assemble into small
Conclusion : onces the material spreads out of the R.L. it forms agregates

Implication for rings

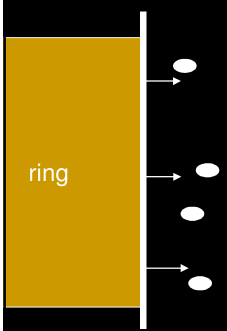
- Very massive initial rings (100x today~4 Rhea masses)
- Ring's age ⇔ Rhea age (~ 3GY)
- Saturn 's A ring : asymptotic state of main rings

SOLVES
- Darkening problem of the rings
- Missing silicates in Saturn rings
  may be inside the moons
(Rhea & Dione in majority)



CAVEATS
- Simple model

Satellite accretion from ring material : Instantaneous accretio @Roche limit (timescale splitting)



When the disk spreads beyond
the Roche Limit (sense of Canup & Esposito 1995)
⇒A satellite is formed

Accretion among moonlets :
Simple statistical criterion (Karjaleinen 2007 for agregates)

In summary : the fate of silicate chunks

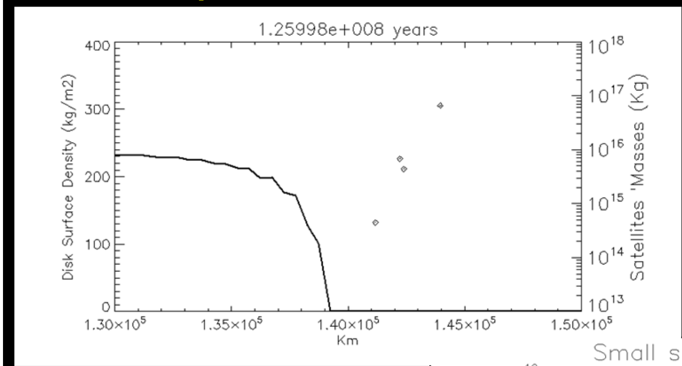
A rough picture…. ???

*** Large chunks (> Mimas) : leave first =>big moons**

*** Small chunks : leave in second => inside big moons**
Or inside Pan, Atlas (the « dense » chard)

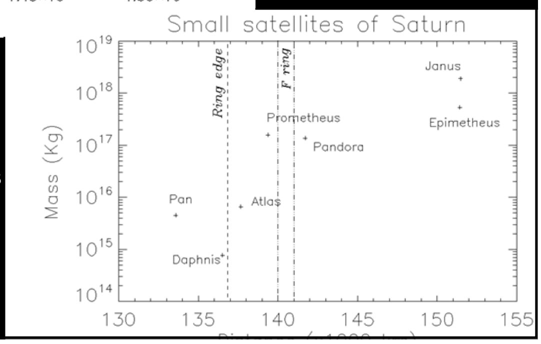
*** Very small chunk : still inside the rings**
(parent bodies of propellers ???)

Implication : Masses and orbital architecture



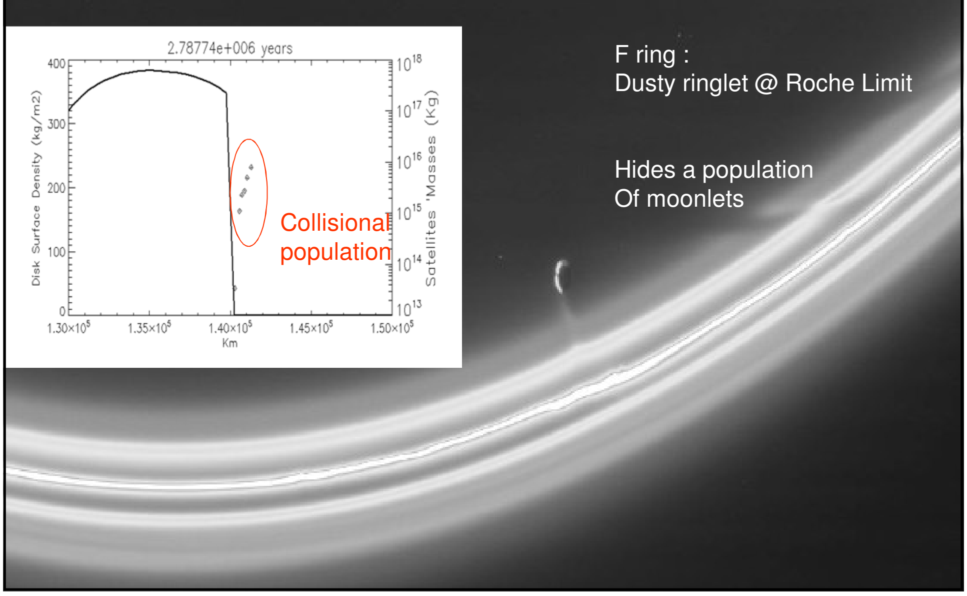
- Size of satellites increases with radial distance

- Mass of moons in ~ good agreements



Implication : Origin of Saturn's F ring ?

At T= 10^6 years : A population of moonlets that may form the F ring



CONCLUSION
A preliminary model for a new type of object: « ring born satellites »

Consistent with

✓ The mass , shapes and spectral properties of the moonlets

✓ The mass Vs. Distance relation

☞ The confinement of the rings' outer edge

☞ The origin of the F ring = product of viscous evolution ??

Open Questions and future work

- Need for a better dynamical model
- Effect of Meteoritic bombardment ?

ACCRETION MAY BE ON-GOING AT THE RING EDGE

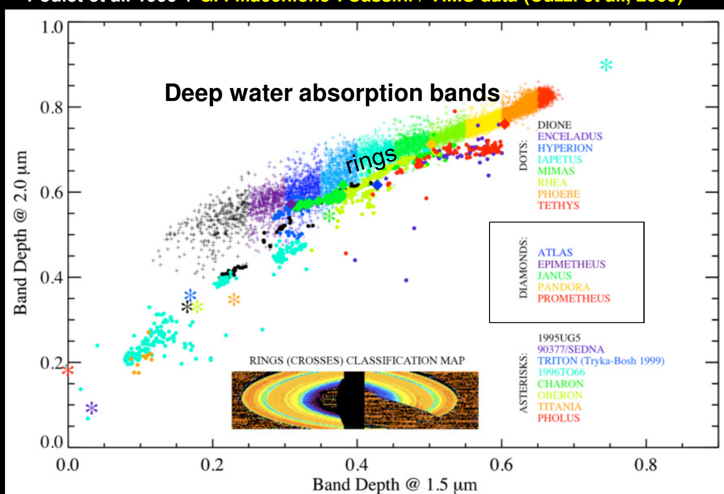
SATURN'S SMALL SATELLITES MAY HAVE RECENTLY ACCRETED

charnoz@cea.fr

THE END

Spectral similarities with rings

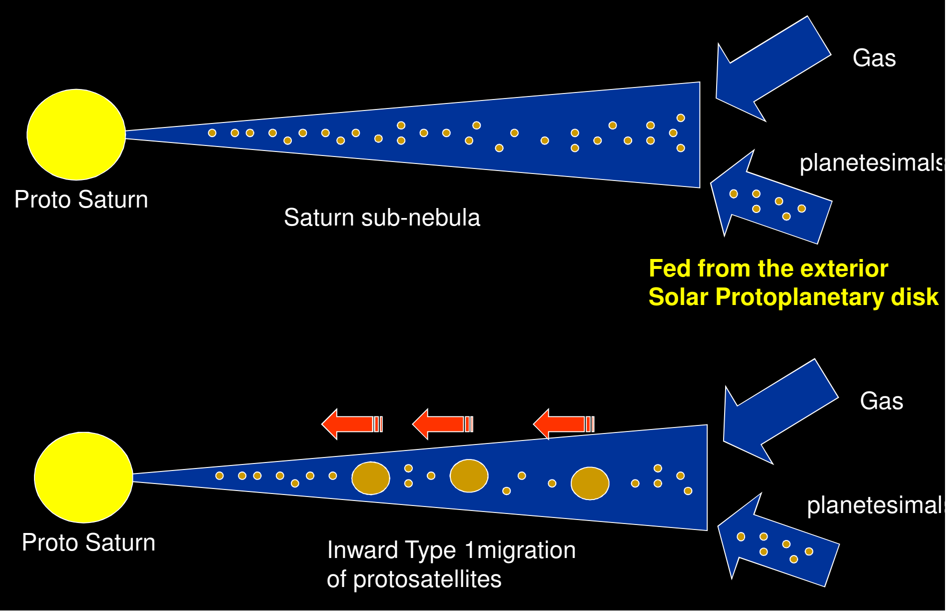
Poulet et al. 1999 + G. Fillacchione : Cassini / VIMS data (Cuzzi et al., 2009)



Absence of silicates => only water ice detectable
Work of Poulet et al.
Nicholson et al.

Formation of main Saturn's satellites : ~ planetary formation

Work of Canup, Ward, Estrada, Mosqueira, and others



Physical characteristics

LOW DENSITIES

obtained from satellite masses, and modeled ellipsoidal shapes and given in gm/cm³. Fitted ellipsoid dimensions for Pan and Atlas with ridges removed are still like flying saucers: 15.9, 15.1, 10.7 km, and 16.9, 16.0, 9.3 km, respectively.

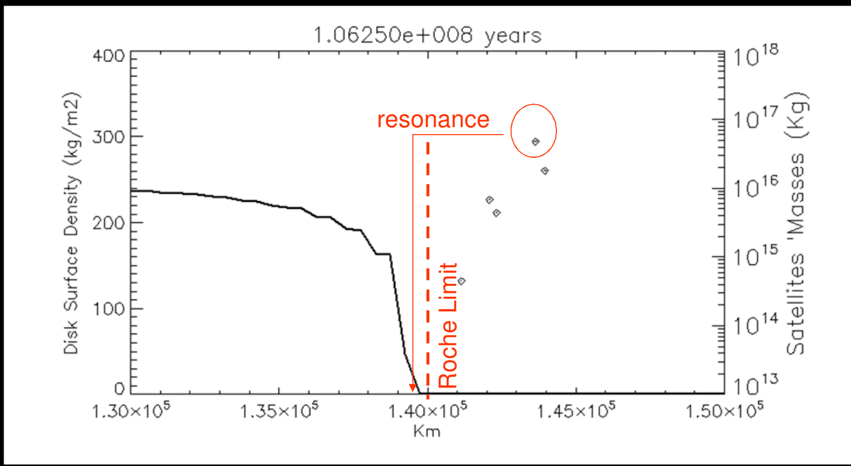
Satellite	$a_{orbital}$	Mass	r_m	a	b	c	± a,b,c	c/a	a_R	$b_R = c_R$	a/a_R	ρ_{crit}	ρ	$\bar{\rho}/\rho_{crit}$
Pan	133584	.495±.075	14.2 ± 1.3	17.4	15.8	10.4	2.0,1.3,.84	0.60	19.1	12.7	0.91	0.45	0.41 ± 0.15	0.92±0.32
Daphnis	136504	.0077±.0015	3.9 ± 0.8	4.5	4.3	3.1	0.8,0.8,0.9	0.69	4.9	3.2	0.93	0.42	0.31 ± 0.20	0.73±0.47
Atlas	137670	.66±.06	15.1 ± 1.4	20.9	18.1	8.9	1.4,2.5,0.8	0.43	21.6	14.4	0.97	0.41	0.46 ± 0.10	1.12±0.24
Prometheus	139380	15.68±.20	43.1 ± 2.7	66.3	39.5	30.7	3.2,3.2,2.0	0.46	62.9	41.9	1.05	0.40	0.47 ± 0.065	1.18±0.17
Pandora	141720	13.58±.23	40.3 ± 2.2	51.6	39.8	32.0	1.8,2.1,2.9	0.62	61.0	40.7	0.85	0.38	0.50 ± 0.085	1.32±0.23
Epimetheus	151410	53.10±.14	56.7 ± 1.9	58.0	58.7	53.2	2.5,3.2,0.8	0.92	102.7	68.4	0.57	0.31	0.69 ± 0.13	2.25±0.42
Janus	151460	191.37±.005	89.6 ± 2.0	97.4	96.9	76.2	2.9,2.2,1.2	0.78	157.4	105	0.62	0.31	0.64 ± 0.064	2.06±0.21
Methone	194440		1.6 ± 0.6				0.6	--				0.15		
Pallene	212280		2.2 ± 0.3	2.6	2.2	1.8	0.4,0.3,0.2	0.69				0.11		
Telesto	294710		12.4 ± 0.4	15.7	11.7	10.4	0.6,0.3,0.3	0.66	--	--	--	0.04	--	
Calypso	294710		10.6 ± 0.7	15.0	11.5	7	0.3,2.3,0.6	0.47	--	--	--	0.04	--	
Polydeuces	377200		1.3 ± 0.4	1.5	1.2	1.0	0.6,0.4,0.2	0.67				0.02		
Helene	377420		16.5 ± 0.6	19.4	18.5	12.3	0.2,1.0,1.0	0.63				0.02		

Porco et al., Science 2007

Mean Density ~ 600 Kg/M³

SELF RAGULATING PROCESS

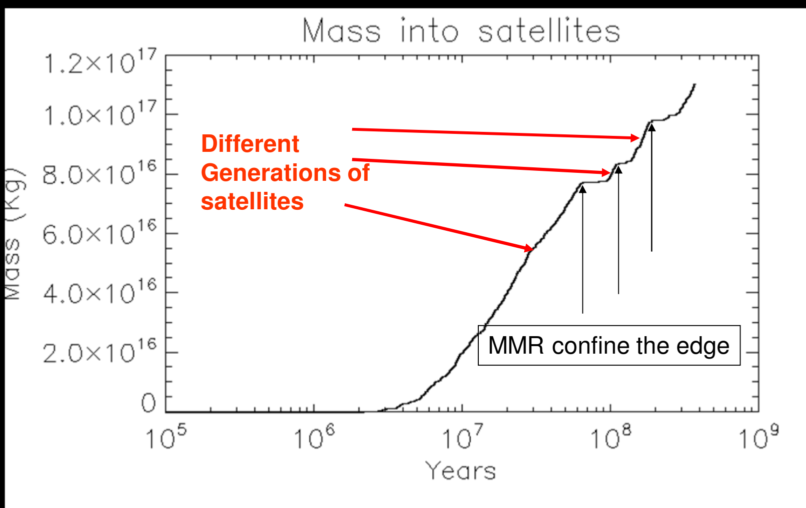
At t=10^8 years : the biggest moonlets repeals the ring inward the Roche Limit : The accretion process stops !



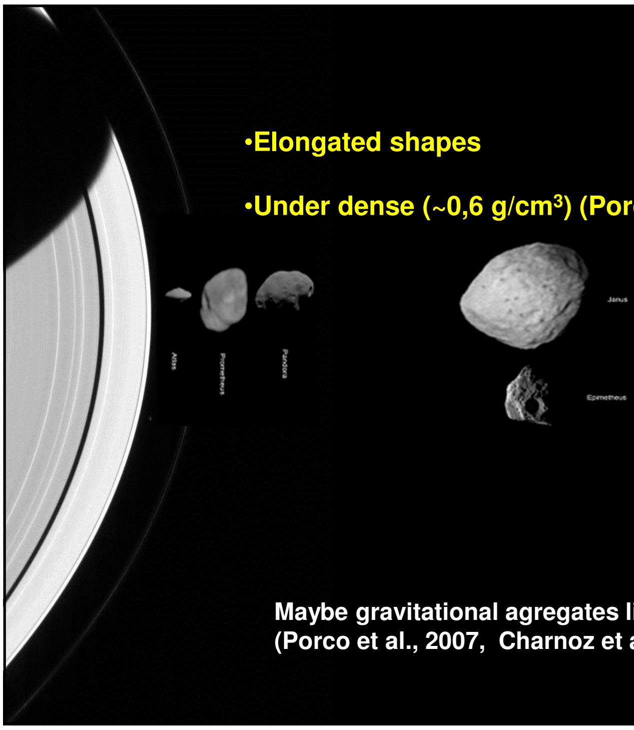
⇒The most massive moon has just enough mass to confine the ring edge : Once it forms he production of satellite stops

Birth of several generations of satellites :

Birth control :MMR Resonances confining or leaving the edge



Physical characteristics



- Elongated shapes
- Under dense (~0,6 g/cm^3) (Porco et al., 2007)

Maybe gravitational agregates like rubble piles (Porco et al., 2007, Charnoz et al., 2007)

Physical characteristics

Mass Vs. Distance relation

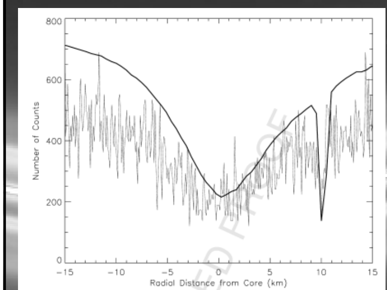
Maybe 2 distinct dynamical/ Accretional regimes ?

puzzling dynamical properties

The F ring

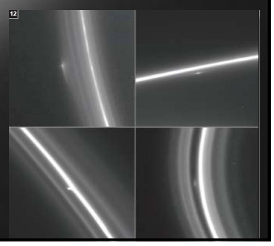
• numerous population of moonlets
(Work of Porco 2005, Murray et al. 2008, Esposito et al. 2008)
Agregates in the ring core

• Near the « Roche Limit » (in the meaning of Canup & Esposito 1995)

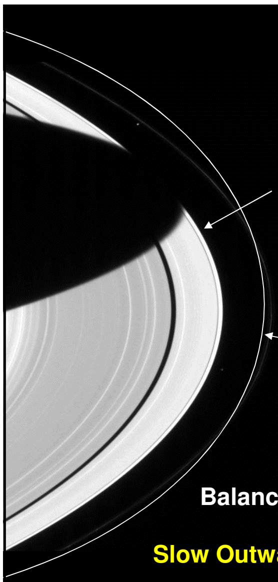


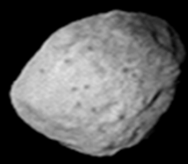
Esposito et al., 2008

Moonlers/clumps



Confinement of the A ring edge by the 7:6 ILR resonance of Janus





Balance : Viscous Torque + Resonant torque =>

Slow Outward motion of the edge + the satellite

=> In ~ 3 10^6 to 3 10^8 years (Lissaeur & Cuzzi 1992 with New Cassini Data)

=> BUT the « Roche Limit » (Sense of C&E 87) is reached in < 10^6 years

The Satellite Torque on the disk

1- Sum on all 1st order resonances up to the satellites ' Hill sphere

2- 2 regimes of resonances

Isolated res : $$|\Gamma_m| \sim f m^2 \Sigma_0 a_s^4 \omega_s^2 \left(\frac{M_s}{M_p}\right)^2 \quad (47a)$$

Overlapping res : $$\left|\frac{d\Gamma}{dr}\right| \sim f' \Sigma_0 a_S^3 \omega_S^2 \left(\frac{M_S}{M_p}\right)^2 \left(\frac{a_S}{r - a_S}\right)^4 \quad (47b)$$

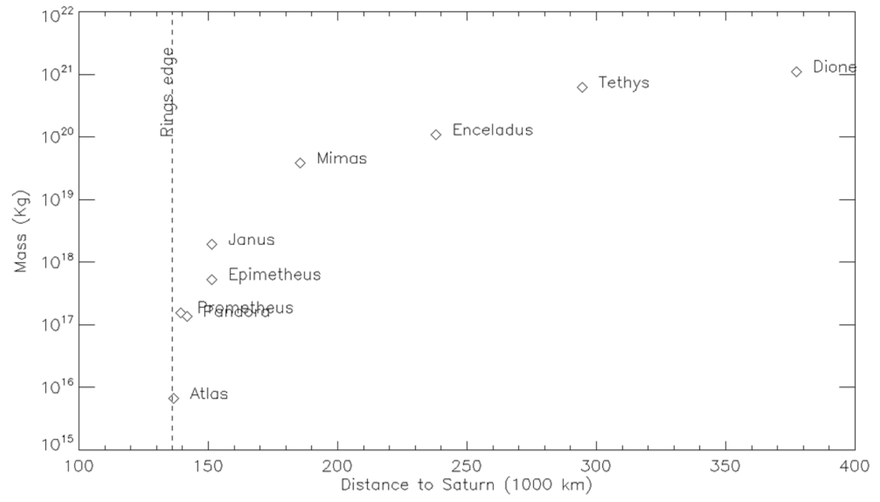
(Meyer-Vernet, Sicardy 1987)

Test the validity of the code :Could reprodiuce

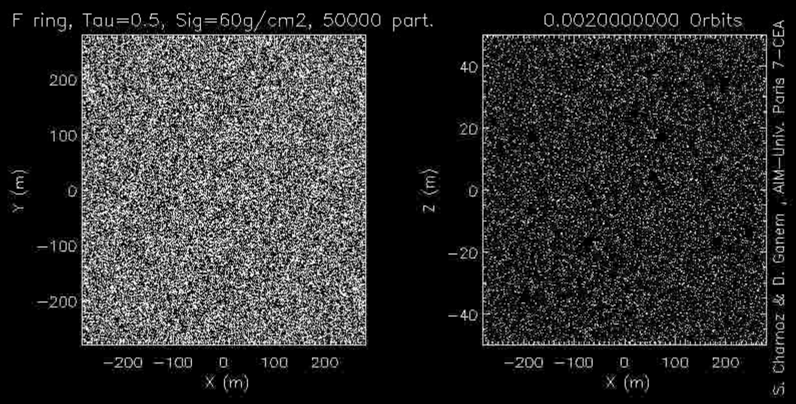
Gap opening, edge confinment, Type 1 migration , Type 2 migration etc…

Physical characteristics

Mass Vs. Distance



Exemple : Local simulation of the A portion of the ring @ 140000 km :
Beyond the Roche limit

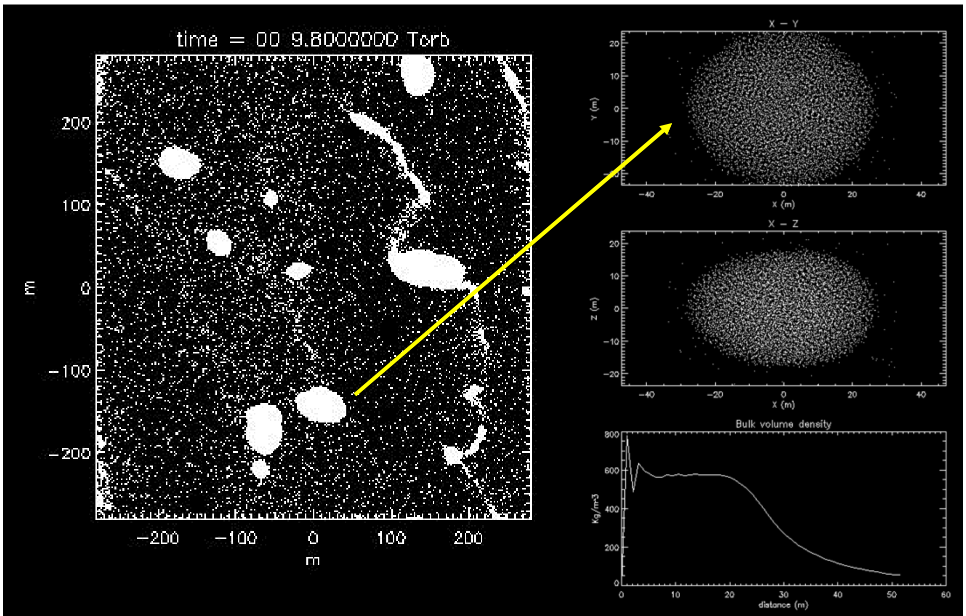


Ring box seen from above

Ring box seen from the edge

Simulation : S. Charnoz

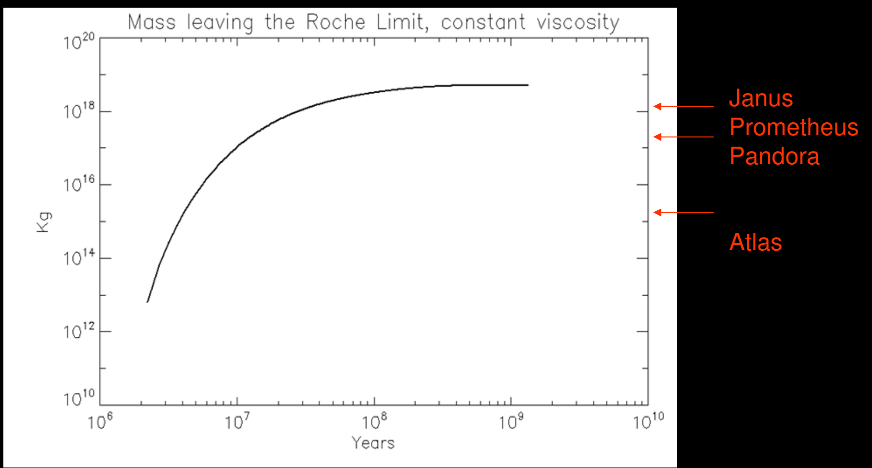
Saturn grav. Field + Particle collisions + Self gravity



Agregates are created rapidly…and assemble into small

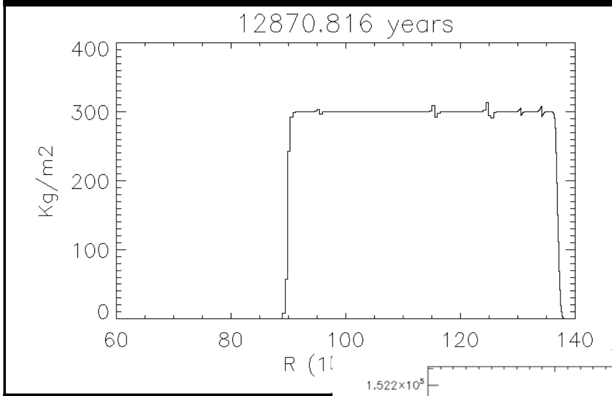
Conclusion : onces the material spreads out of the R.L. it forms agregates

Like any astrophysical disk : Saturn rings spread when they are not confined (work of Salmon et al.)



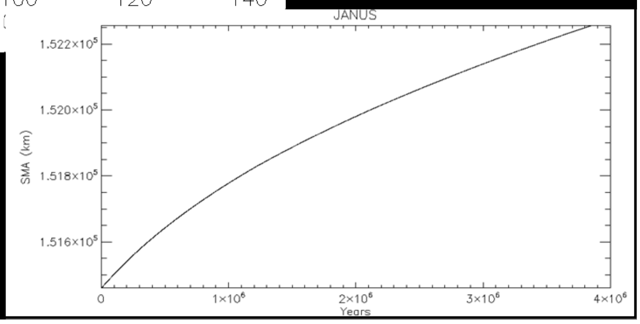
About a mass comparable to the present population's mass spreads out of the ring's Roche limit in $> 10^8$ years

Simulation of Janus interacting with the ring system (simple model)



Charnoz et al., 2009

A testcase



A fragile equilibrium

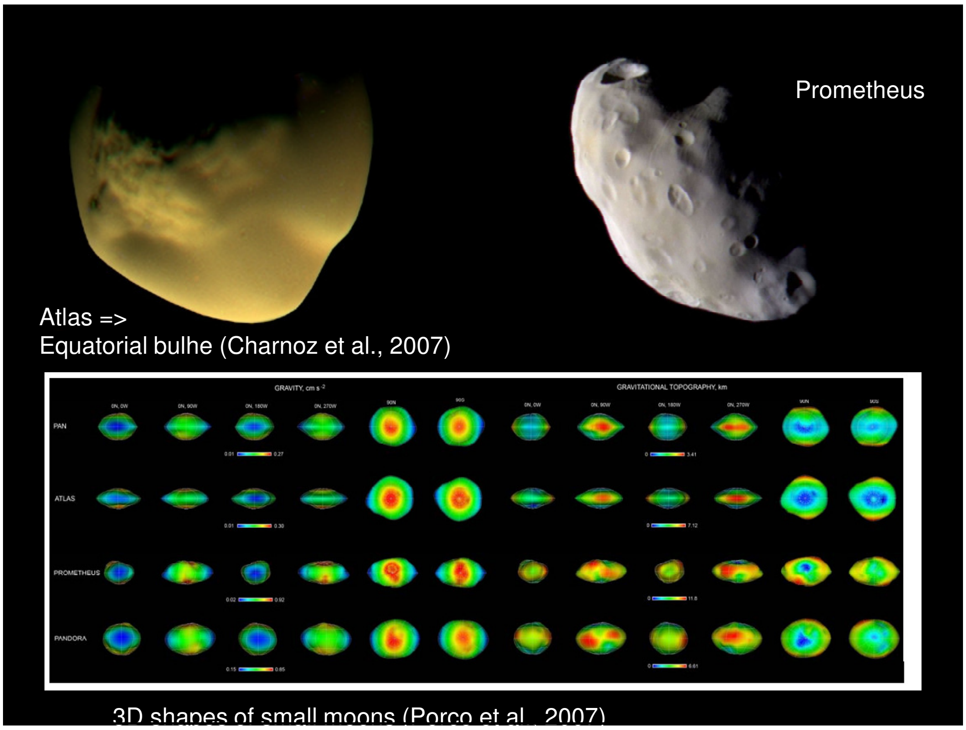
1. Janus moves outward on a 10^6 to 10^7 years timescale

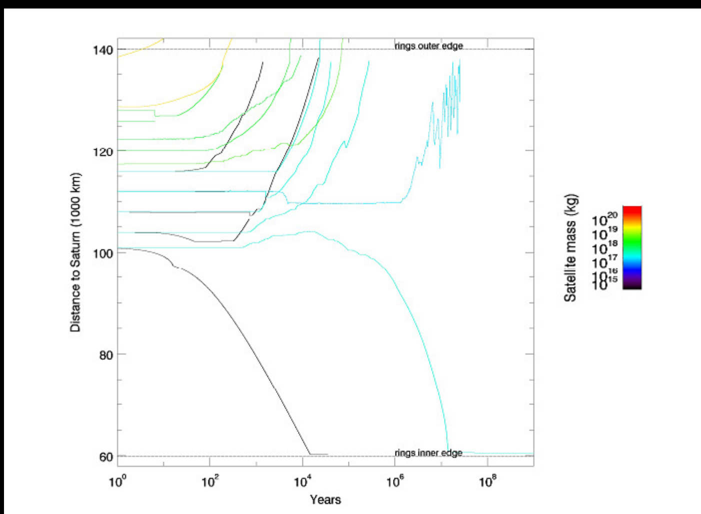
Because of : Rings 'torque + Saturn's tidal torque

⇒ T_outward =A/da/dt of is about 10^7 years (Lissauer & Cuzzi 1992)

⇒The 7:6 resonance will quit the ring (and a new one will arrive)
=> The A ring will be free to spread

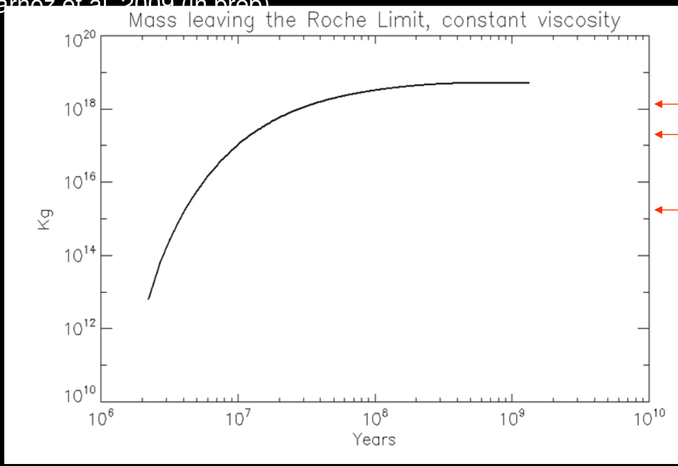
2. In the past the satellite may have been closer to Saturn => the 7:6 resonance Would have not maintained the ring edge


Prometheus
Atlas =>
Equatorial bulhe (Charnoz et al., 2007)
GRAVITY, cm s-2
GRAVITATIONAL TOPOGRAPHY, km
PAN
ATLAS
PROMETHEUS
PANDORA
3D shapes of small moons (Porco et al., 2007)


rings outer edge
rings inner edge
140
120
100
80
60
Distance to Saturn (1000 km)
10^0
10^2
10^4
10^6
10^8
Years
Satellite mass (kg)
10^20
10^19
10^18
10^17
10^16
10^15

Like any astrophysical disk : Saturn rings will spread

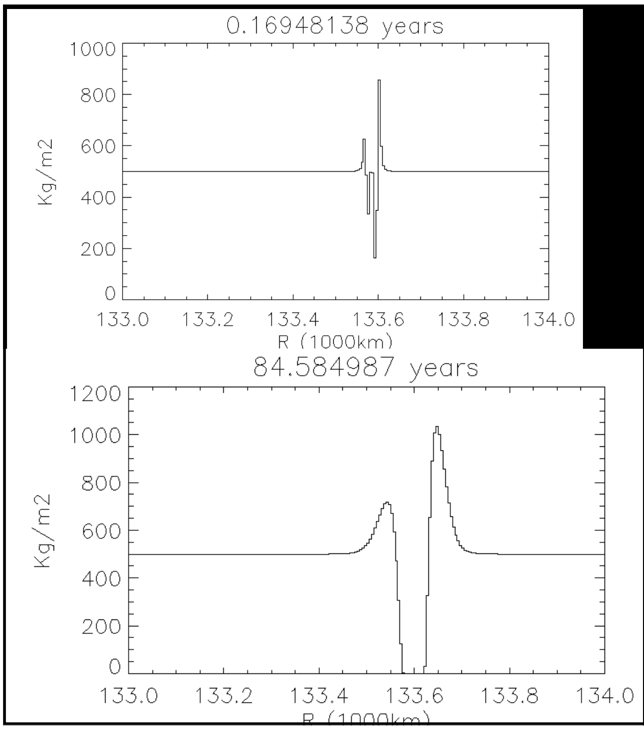
Charnoz et al. 2009 (in prep)



Janus
Prometheus
Pandora

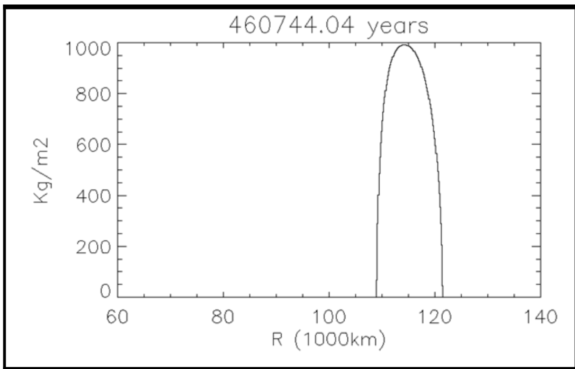
Atlas

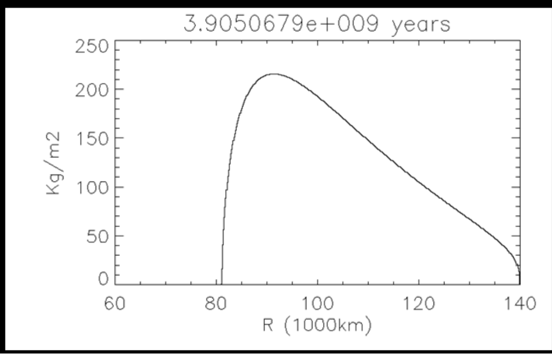
About a mass comparable to the present population's mass spreads out of the ring's Roche limit in > 10^8 years



Exemple 1

Pan
Gap openning

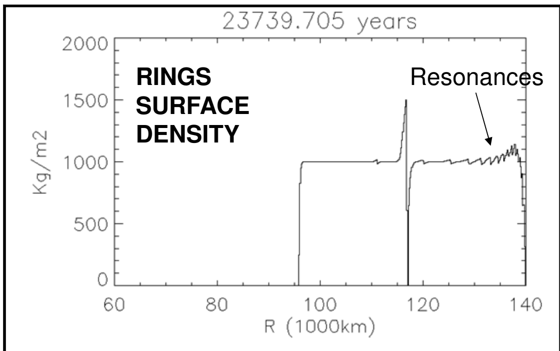




Spreading of
A ringlet

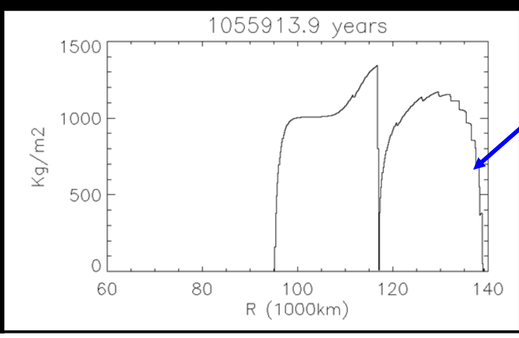
⇒Non constant viscosity

(Daisaka et al., 2001)

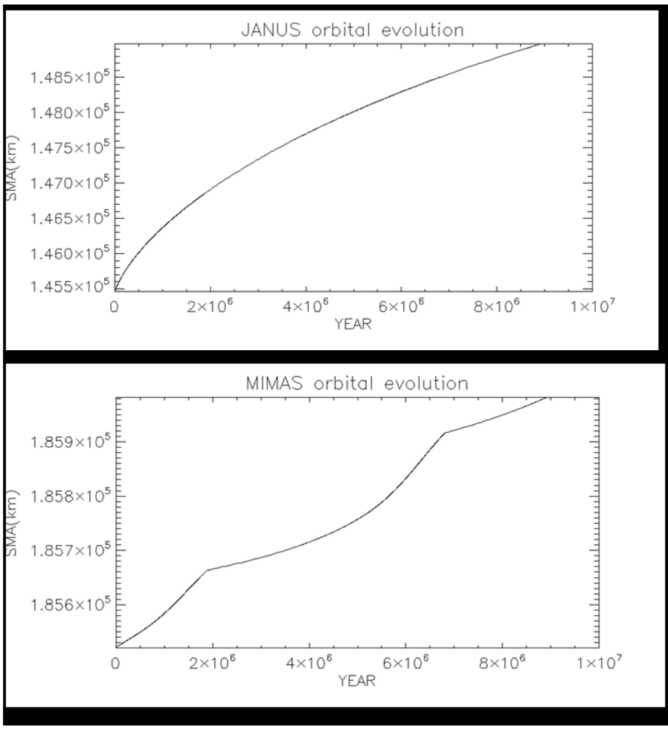


Exemple without accretion :

Effect of Janus + Mimas+ Disk



The disk is pushed inward by Janus



Outward migration
Of Janus and Mimas

Physical characteristics

A relation that may even extend below the Roche Limit ?