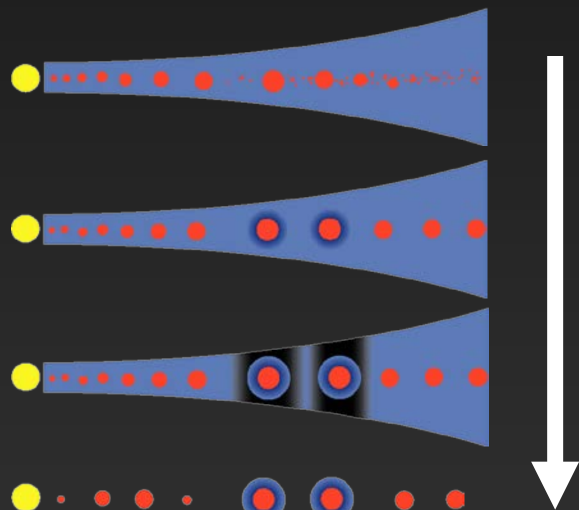
衛星系形成過程のレビュー
（と最近の話題）

谷川　享行

北海道大学　低温科学研究所

Formation of Giant Planets

Giant planet formation



Solid planets (~10 Earth masses)

Instability of the atmosphere

Onset of gas accretion

Gap formation

Dissipation of the disk

Satellites are thought to be formed at very end of the formation of gas-giant planets

What is a Satellite System?

– Systems that consist of multiple objects rotating around planets

– Generally exist around gas giant planets

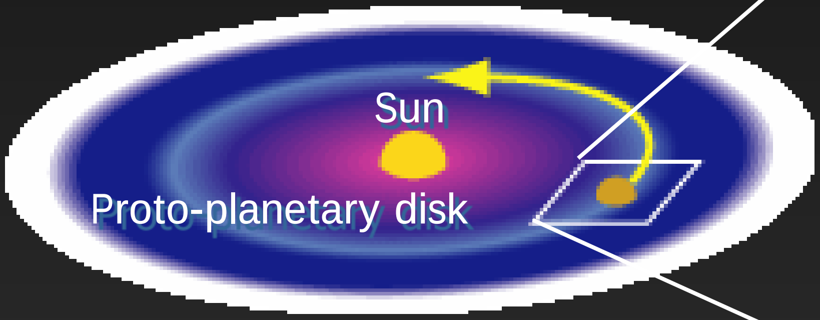
– Regular satellites and irregular satellites

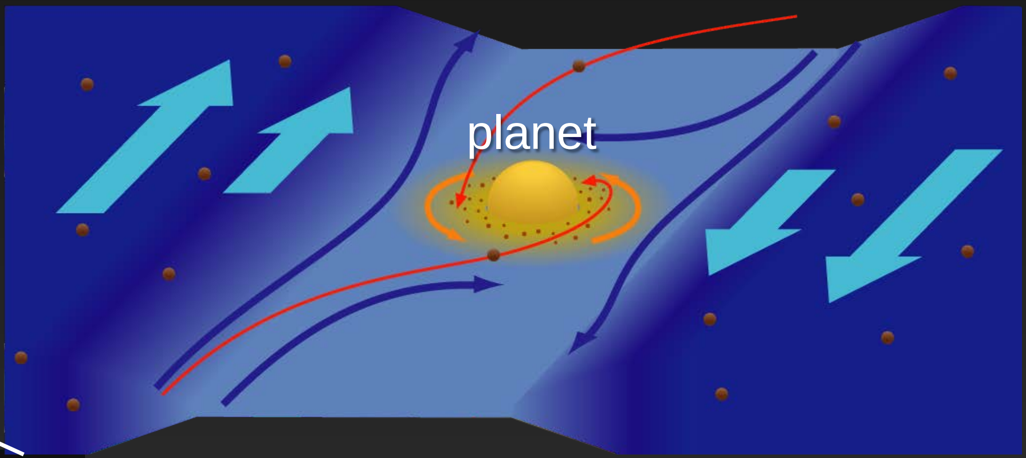
- Regular satellites:
  – Nearly circular orbits, orbital plane ~= equatorial plane
  – Account for most of the total mass of satellites
- → Formed from circum-planetary disks?

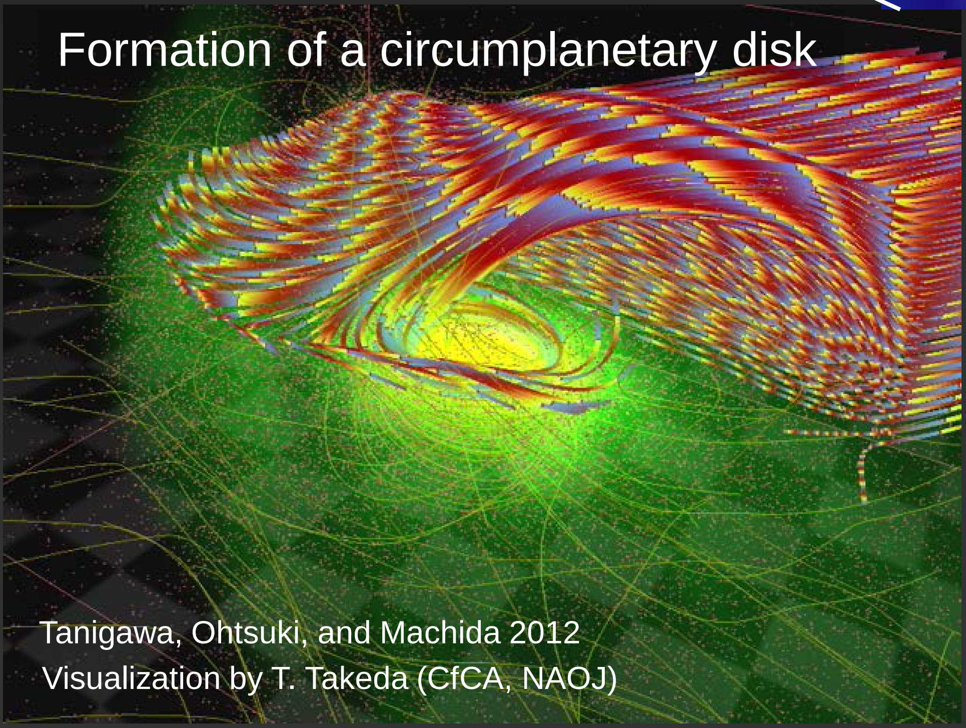
Satellites of outer planets


Jupiter and Galilean satellites

What is Circum-Planetary Disk?







- Circumplanetary disks are natural by-products of giant planet formation
- Gas is accreted downward from above, not through the midplane.

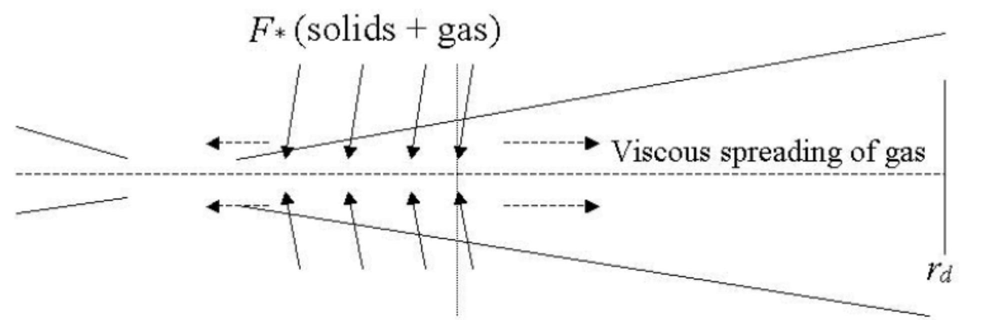
“Classical” Minimum Mass Sub-Nebula Model

- 現在の衛星総質量 ~ 10-4 Mp のダストとその約100倍のガスからなる円盤を初期条件
  - 当時(?)の太陽系形成理論に準じている
  - 最初から衛星総質量をもつ重い円盤

- 問題点
  - 高過ぎる面密度
  - → 円盤温度高温 → H2O が気相になり、材料物質として使えない
  - → 速すぎる集積時間 → 大きな集積熱 → カリストの未分化説明不可
  - → 速すぎる Type I 移動 → 衛星が出来ても惑星へ落下

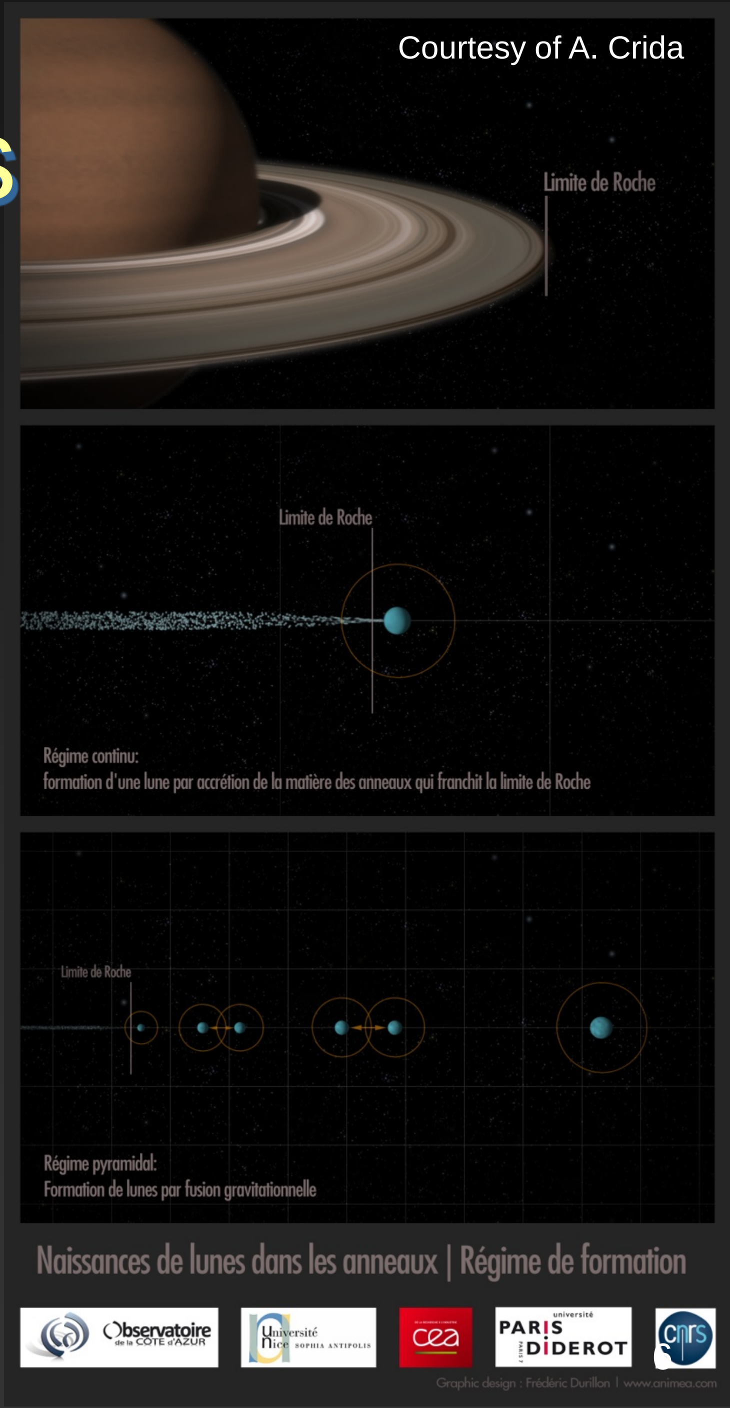
Two plausible models

- Gas-starved disk model
  - Canup and Ward 2002, 2006



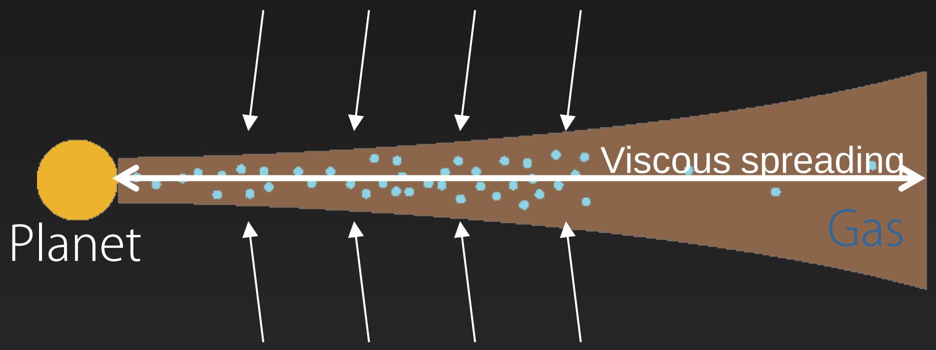
Canup and Ward 2002

- Spreading tidal-disk model
  - Crida and Charnoz 2012



Gas-starved disk model

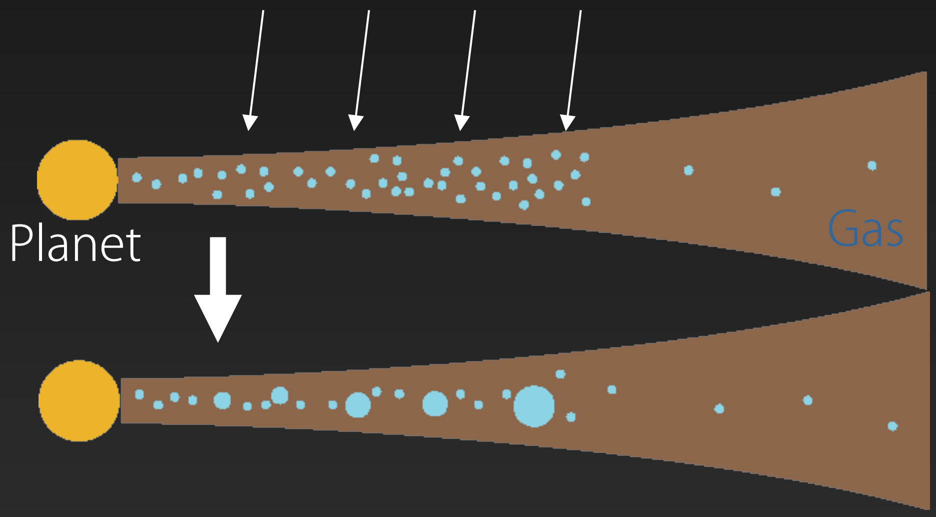
Canup and Ward 2002, 2006



Steady mass supply

Gas-starved disk model

Canup and Ward 2002, 2006

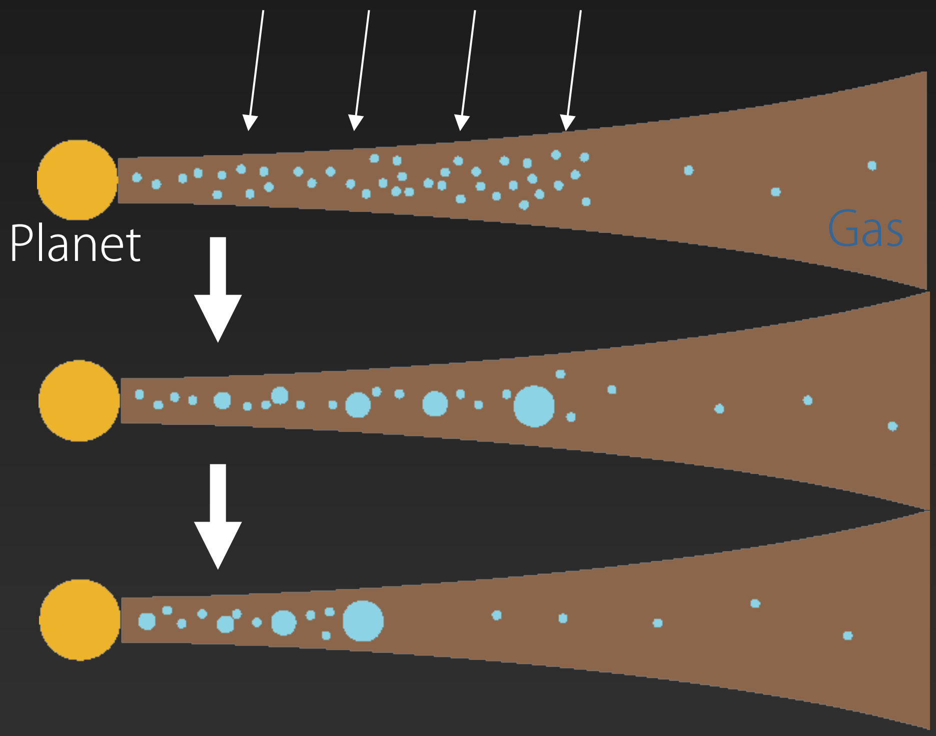


Steady mass supply

Growth from outside

Gas-starved disk model

Canup and Ward 2002, 2006



Steady mass supply

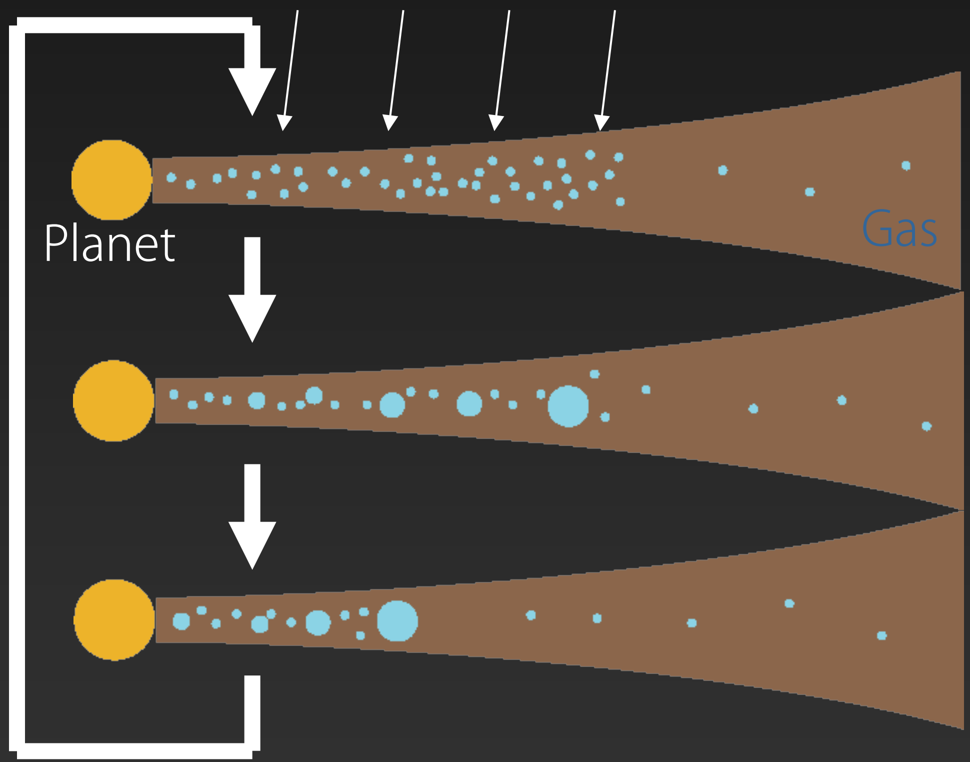
Growth from outside

Larger satellites move inward

Inner objects are swept

Gas-starved disk model

Canup and Ward 2002, 2006



Steady mass supply

Growth from outside

Larger planets move inward

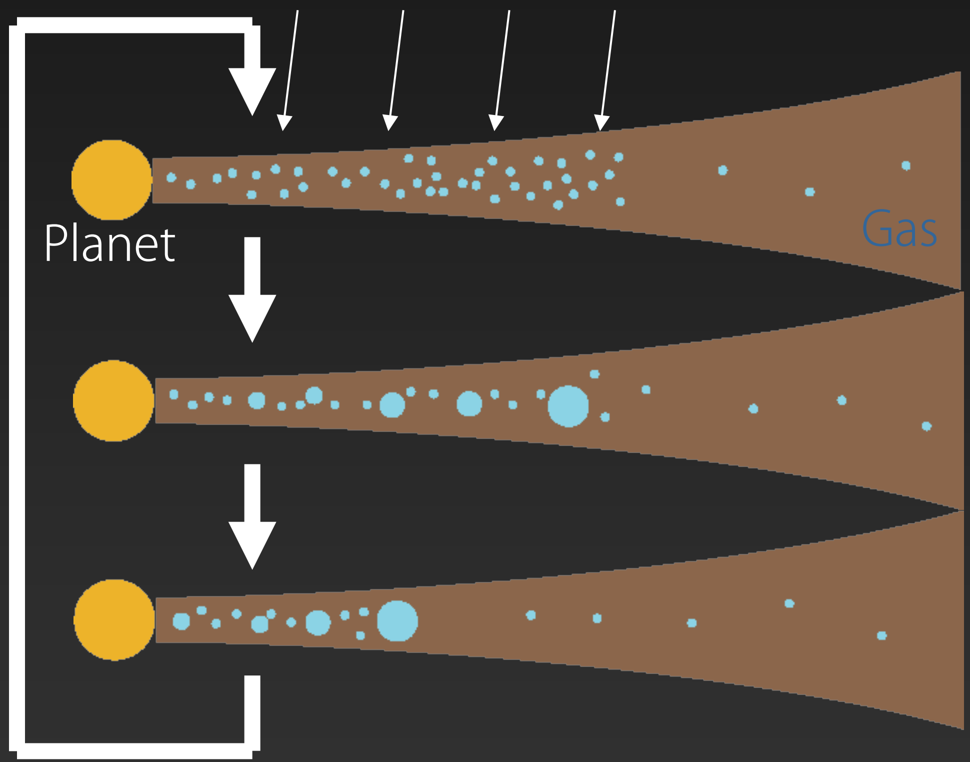
Inner objects are swept

Continue until the mass supply terminates.

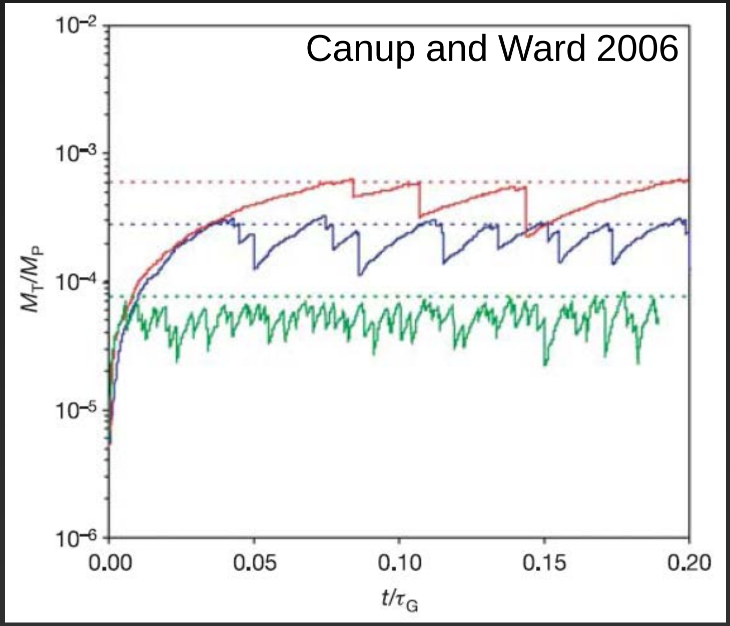
Current satellites are the last generation of this cycle

Gas-starved disk model

Canup and Ward 2002, 2006



Total mass of satellites / planet mass



Size (mass) is automatically determined by the balance between growth and fall

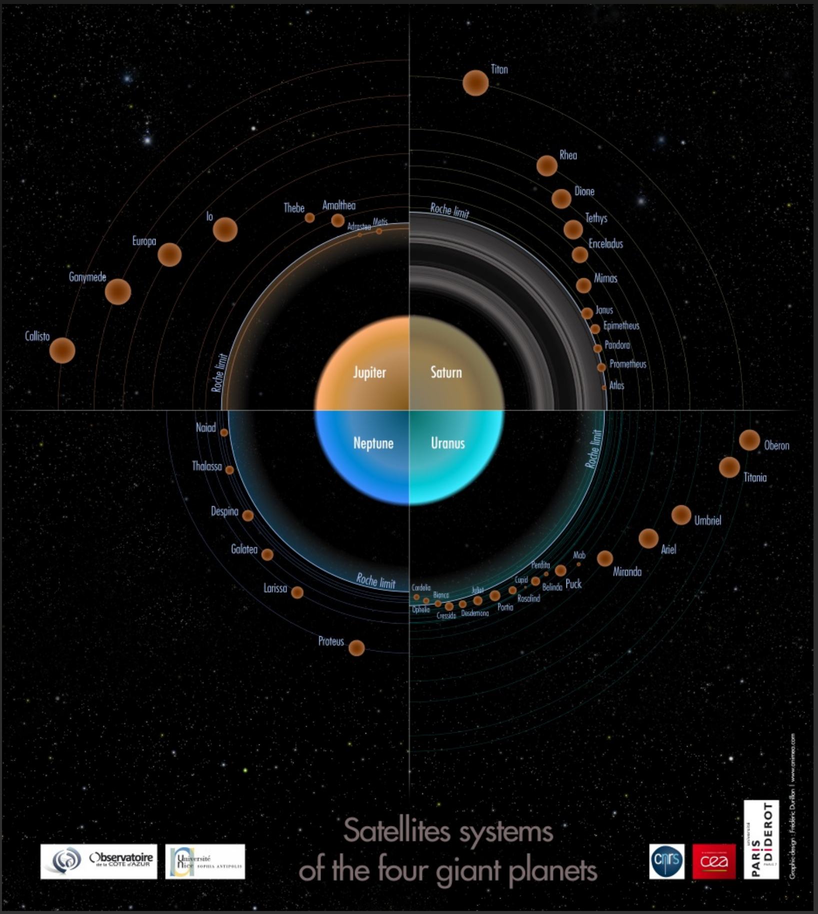
Summary of Gas-starved disk model

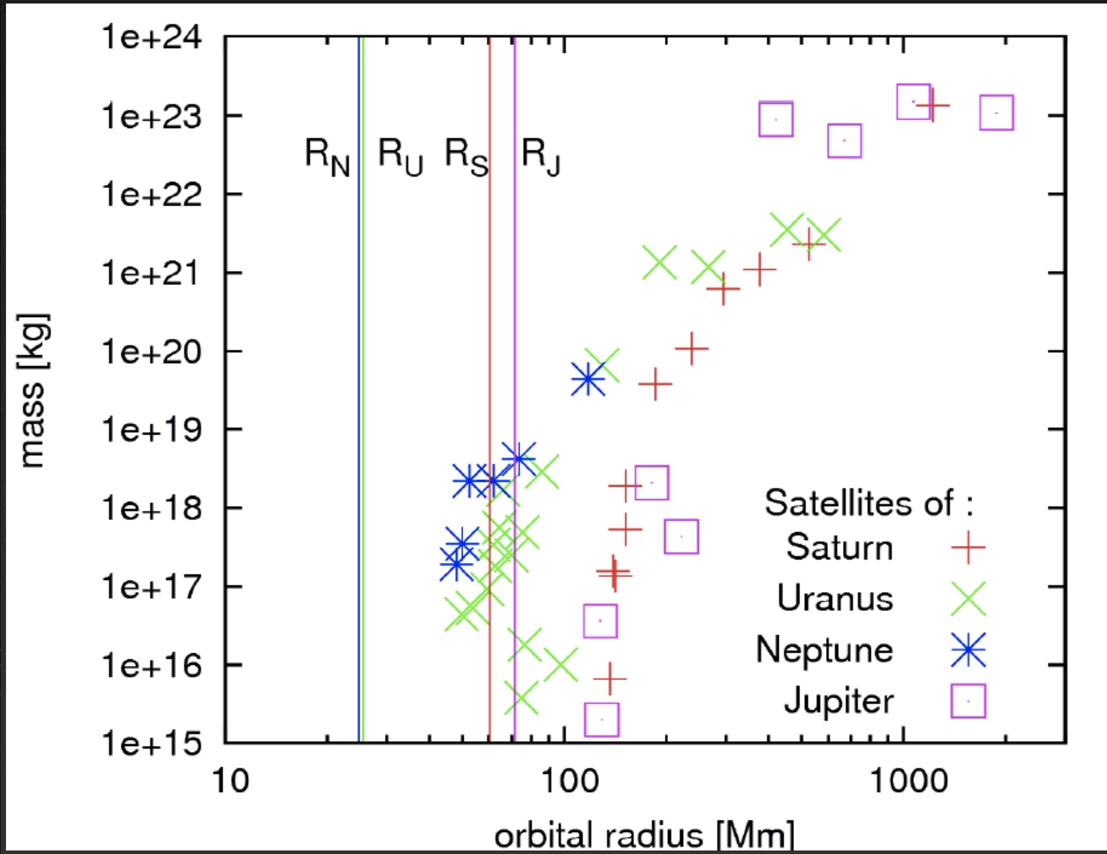
- Looks good!
  - Total mass of the regular satellites
    - Weak dependence on model parameters
  - Partial differentiation of Callisto
  - Rock fraction of Galilean satellites

- Open questions
  - Size distribution of satellites?
    - Difference between Jovian system (4 large moons) and Saturnian system (one large moon and several mid-sized moons)?
    - Whether inner edge exists or not? (Sasaki et al. 2010)
  - How about Neptunian system?
    - Triton (large retrograde satellite)?

Spreading tidal disk model

Crida and Charnoz 2012



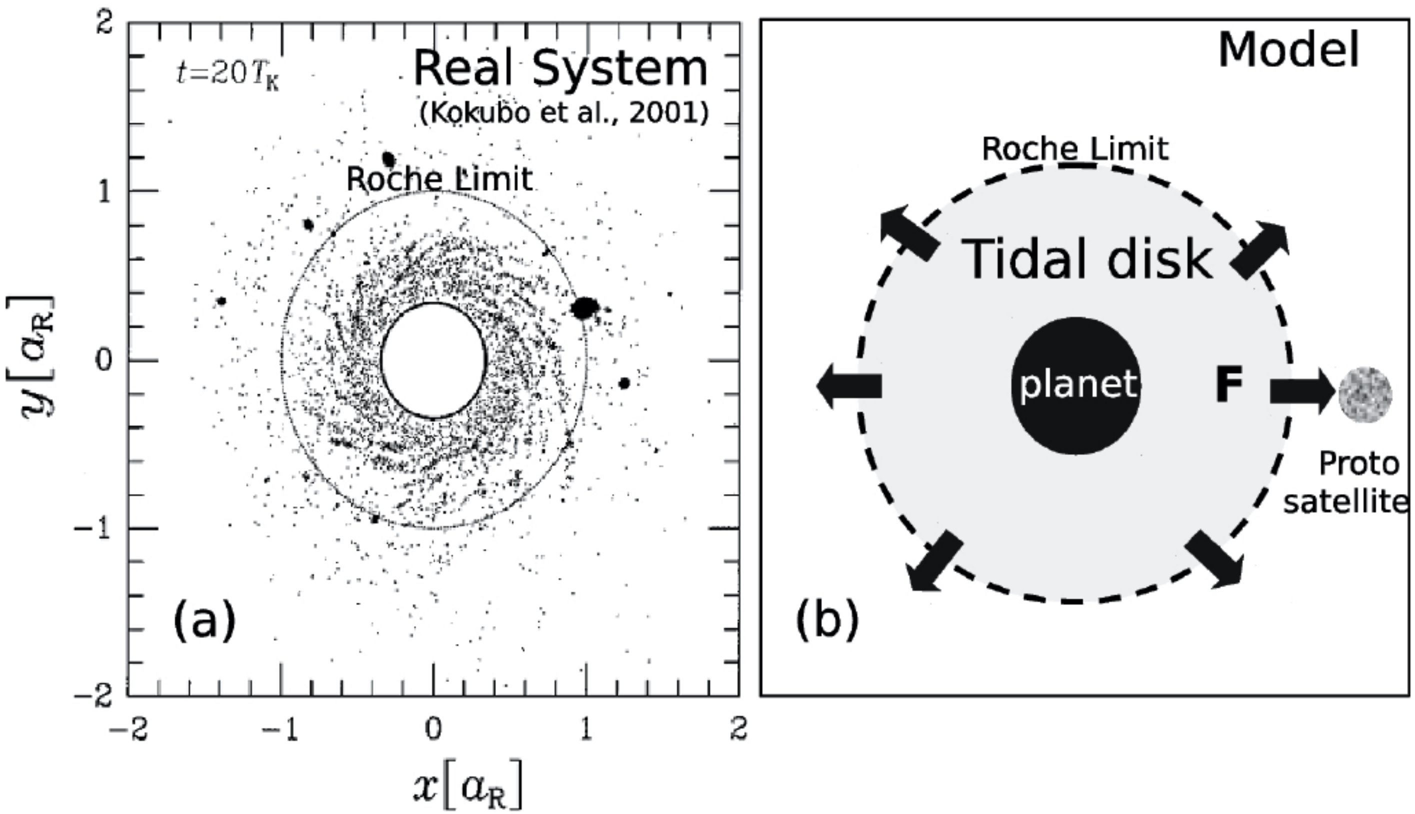


Size increases with orbital radius

Spreading of a tidal disk

Inside the Roche radius r_R, there is a « tidal disk », that spreads with a mass flow **F** (assumed constant).

Beyond r_R, new satellitte(s) form...



Ring viscous evolution model
Salmon et al. 2010

$$\nu = \nu_{\text{trans}} + \nu_{\text{coll}} + \nu_{\text{grav}}$$

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

$$\nu_{\text{coll}} = r_p^2 \Omega \tau \quad \forall Q,$$

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

- Translational viscosity
  - Random motion
  - “local” component
- Collisional viscosity
  - Collision between particles
  - “non-local” component
- Gravitational viscosity
  - Gravity wakes

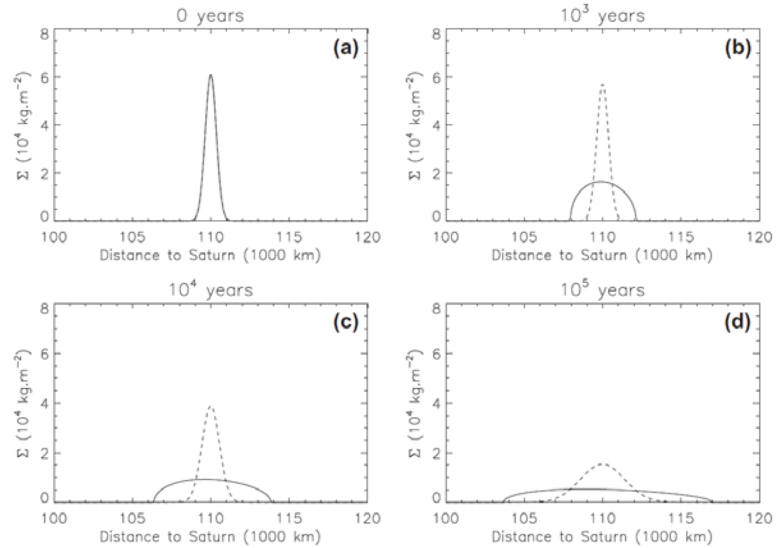
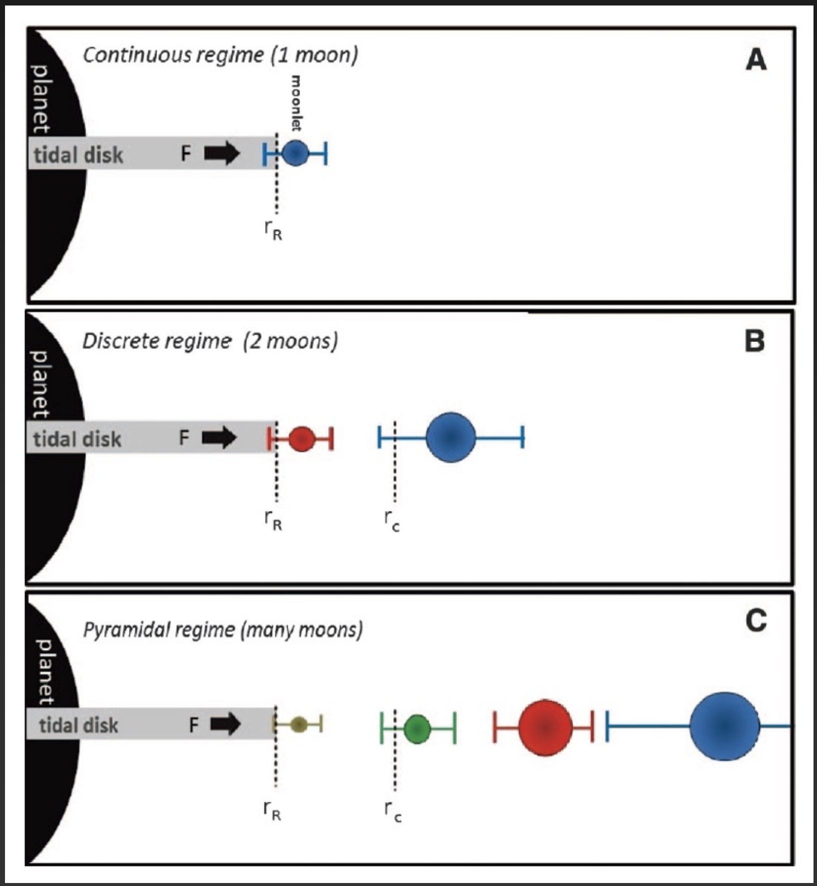


Fig. 3. Disk surface density at different evolution times for variable (solid line) and constant (dashed line) viscosities. (a) Initial profile. (b) At 1000 years of evolution. (c) At 10^4 years of evolution. (d) At 10^5 years of evolution. The disk with variable viscosity spreads faster and does not keep the original shape of the density profile.

Forming process in detail



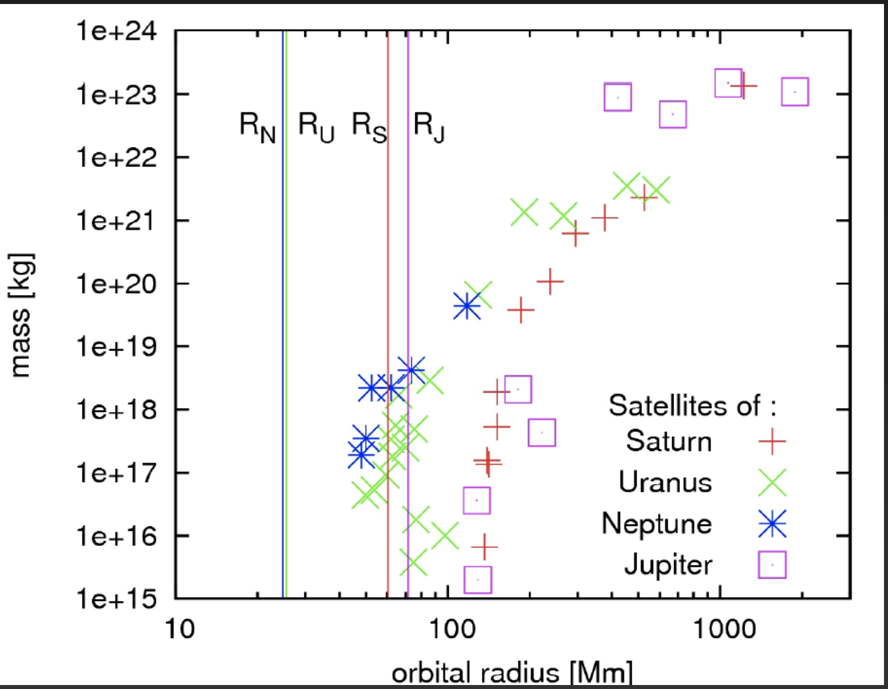
A
- The tidal disk continuously supplies particles beyond Roche radius through viscosity
- Particles outside Roche radius aggregate to be a moonlet
- Tidal torque moves the moonlet outward

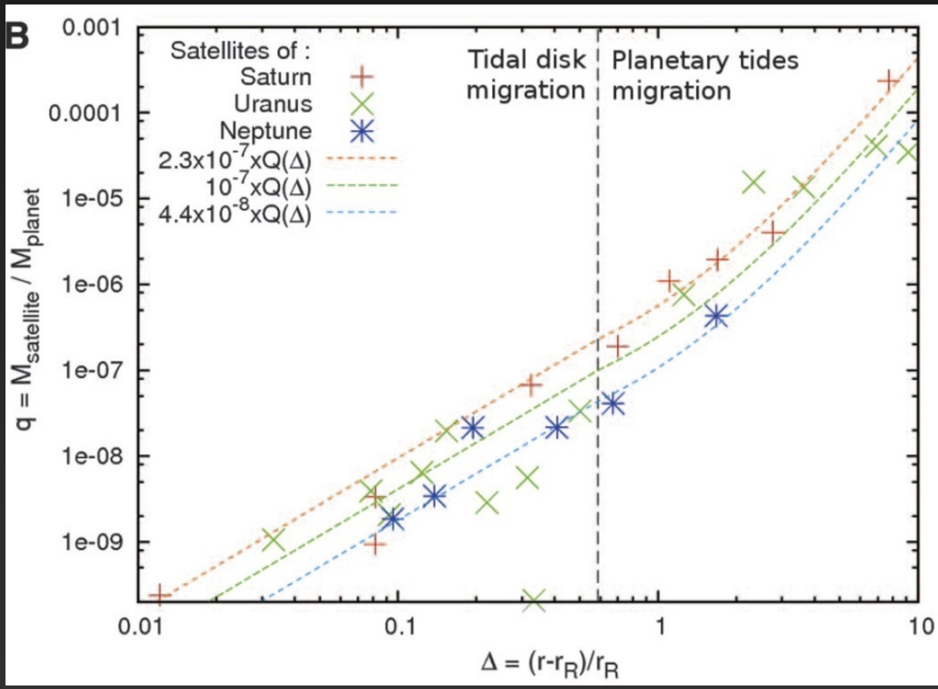
B
- The second moonlet starts to form when the first moon migrates far enough.
- The second moon catch up with the first moon and merge.

C
- Outer moons are easier to be caught up by inner moons and be merged.
  - Farther moons moves slower
  - Larger moons moves faster

→ **Pyramidal size distribution!**

Size distribution





Distance from Roche limit

Summary of Spreading tidal-disk model

- Look better! (maybe)
  - Pyramidal size distribution (not absolute size)
    - Size increases with orbital radius
  - Earth's moon and Charon can also be explain

- Open questions
  - Origin of the tidal disk
    - Disruption of satellites
    - Tidally disrupted comets
  - Jovian system (Galilean satellites)
  - Mutual gravitational interaction between satellites
    - Increase of orbital eccentricity?
  - Density dispersion of Saturnian system
    - Giant impacts? (Sekine and Genda 2012, Asphaug & Reufer 2013)
    - LHB? (Nimmo & Korycansky 2012)
  - Resonance of Saturnian system
    - Mimas-Tethys, Enceladus-Dione

Courtesy of A. Crida

Comparison

	Gas-starved disk model Canup and Ward	Spreading tidal-disk model Crida and Charnoz
Jupiter	△	×
Saturn	○	○
Uranus	○	○
Neptune	△	○

Comparison

	Gas-starved disk model **Canup and Ward**	**Spreading tidal-disk model** **Crida and Charnoz**
Jupiter	△	×
Saturn	○	○
Uranus	○	○
Neptune	△	○
Earth	-	○
Pluto	-	○

Summary

- Two formation models for the satellite systems are reviewed.
  - Gas-starved disk model (Canup and Ward)
    - Total mass of regular satellite systems (not the size distribution)
      - Weak parameter dependence
    - Rock fraction and partial differentiation
    - Size distribution (Galilean satellites)
    - Neptunian system
  - Spreading tidal-disk model (Crida and Charnoz)
    - Pyramidal size distribution (not absolute mass)
    - Earth and Pluto system
    - Origin of tidal disk
    - Jovian system