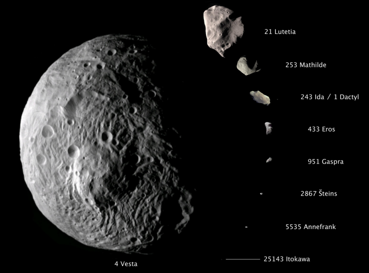
Solar system science in the E-ELT era

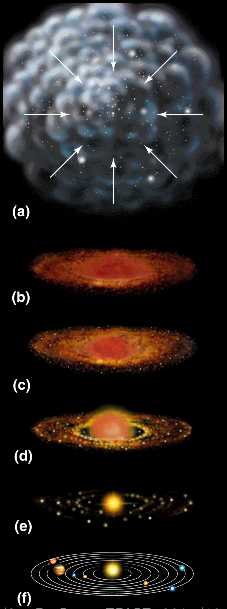


B. Carry[1,2]

[1]IMCCE, Observatoire de Paris
[2]Lagrange, Observatoire de la Côte d'Azur

1. Planetary formation
2. Solar system history
3. Open questions
4. Planets
5. Satellites & rings

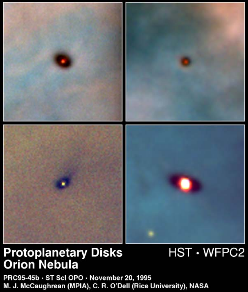
Planetary formation: Sketch

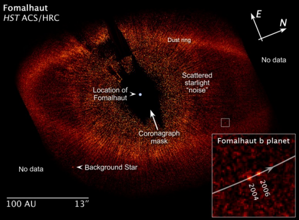


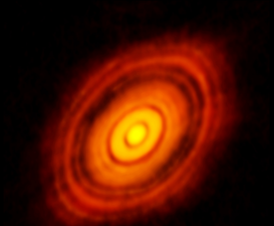
A step-by-step process:

a. Gas & dust cloud contraction
b. Disk formation
c. Rotation, accumulation of material
d. A star is born
e. Accretion within the disk
f. Planetary system

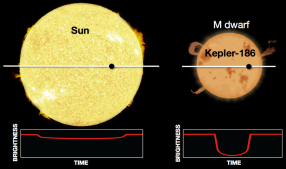
Planetary formation: Examples







ALMA (ESO/NAOJ/NRAO)

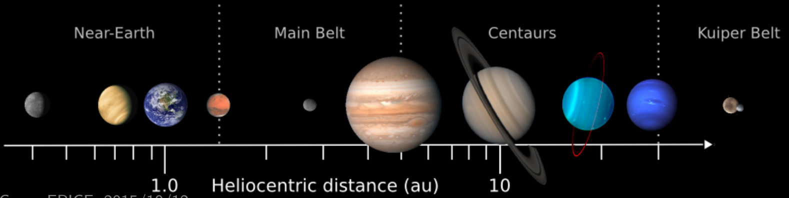


NASA/Kepler/Outreach

Planetary formation: Planets

1. The genuine outcome of planetary formation
   - Giant planets non-zero eccentricity
   - Small Mars
   - Small Uranus & Neptune
2. Evolved surfaces and interiors
   - Endogeneous activity: volcanism, plate tectonic, erosion
   - Lack of evidence on original material
   - Differential evolution of planets

▷ *Oblivious* witnesses of the early Solar System

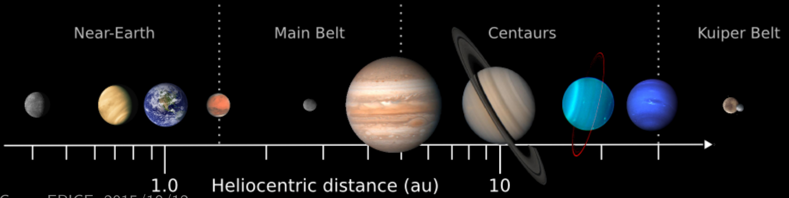


Planetary formation: SSOs

1. Large population
   - 690 000 objects (*several millions*)
   - Wide range of compositions [rocks → ices]
   - Wide range of heliocentric distances [1 → 10^{2-5} au]

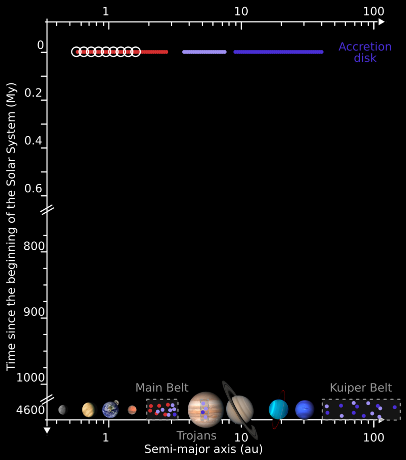
2. Primitive population
   - Small objects [m → 10^3 km]
   - Internal energy ≈ null
   - No endogeneous activity

▷ *Direct* witnesses of the early Solar System



1. Planetary formation
2. **Solar system history**
   - Observational evidences
   - Early event: the Grand Tack
   - Late planetary instability: the Nice model
3. Open questions
4. Planets
5. Satellites & rings

History: Evidences



DeMeo & Carry 2014

A. Accretion disk

- Gas & Dust
- Composition gradient

B. Planets

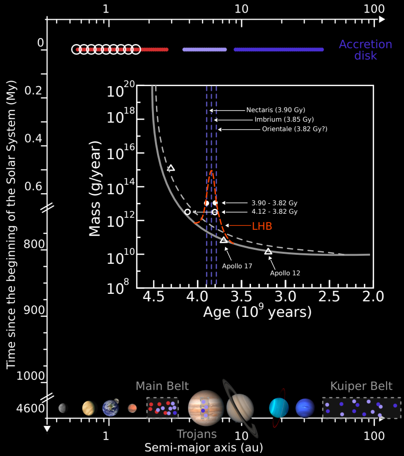
- Relative masses
- Eccentricities
- Compositions

C. Small bodies

- Belts mass & SFD
- Mixed asteroids
- Homogeneous Trojans
- Inclined KBOs

D. Late Heavy Bombardment

History: Evidences



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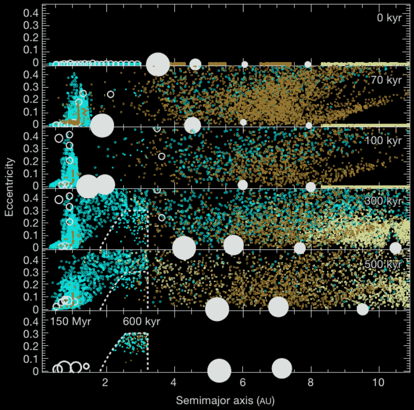
History: Gran Tack



Walsh et al. 2011

A. Jupiter moves inward

- Bowling strike
- Mass of Mars
- Deplete MB

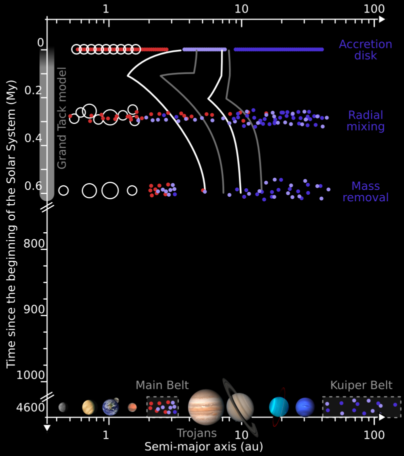
B. Jupiter moves outward

- Excite orbits
- Mix inner → MB

C. Result for **Inner** Solar System

- Complete mixing
- Removal of 99% mass

History: Gran Tack



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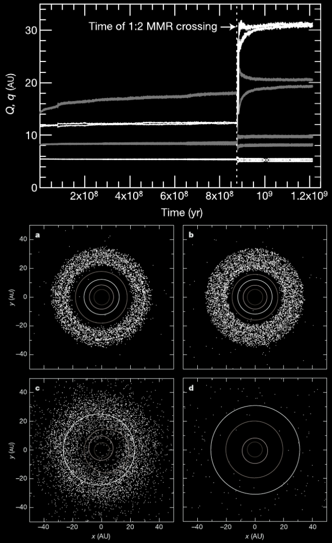


Gomes/Tsiganis/Morbidelli 2005

A. Original idea

- Smooth migration
- Jupiter-Saturn resonance

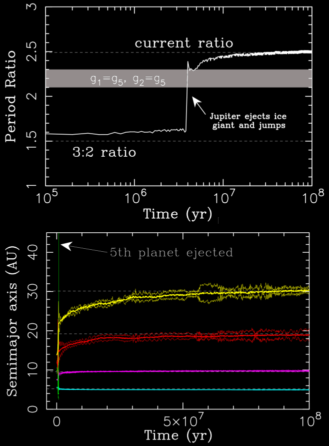
B. New paradigm

- Ice/gas giant interactions
- **Jumping** Jupiter

C. Results for Solar System

- Mix outer → MB
- Trojans replaced
- Satellite captured
- Fifth or sixth giant planet!

History: Nice



Morbidelli et al. 2007/2010+

Nesvorny/Batygin 2011/2012

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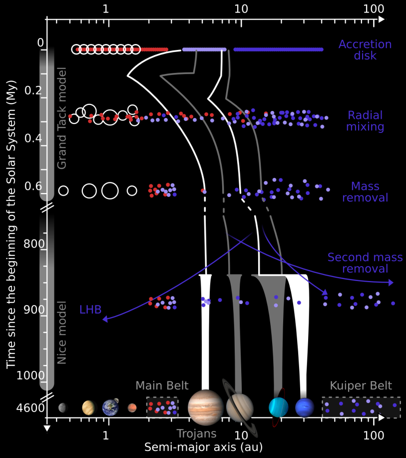

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1. **Planetary formation**
2. **Solar system history**
3. **Open questions**
   - ▷ What are the main open questions in the field?
   - ▷ How do we study them?
4. **Planets**
5. **Satellites & rings**

Key questions

- Details of planetary migrations?
- Origin of Earth water and life?

- Location & timescale of Uranus and Neptune formation?
- Location & timescale of asteroids and comets formation?
- Satellites and rings formation & evolution?

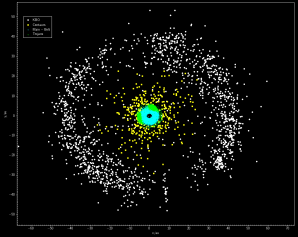
- Mass and SFD of SSOs?
- Composition of asteroids, comets, and meteors?

- Surface alteration?
- Sources of NEAs and meteorites?

- Physical & geometrical properties?
- ...

Answers?

1. Discovery & Census
   - Observation → population
   - New categories of objects
   - Surveys
2. Dynamics: Short & Long-Term
   - Origin & evolution
   - Astrometry
3. Composition
   - Asteroids/Meteors → Mineralogy
   - Comets/KBOs → Volatiles
   - Spectrometry
4. Physical properties
   - Starlike → Worlds
   - Structure: Interior & Surface
   - Imaging



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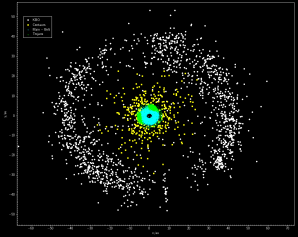

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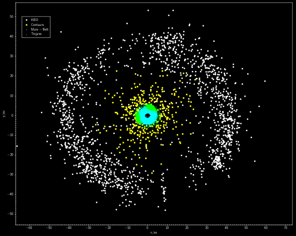

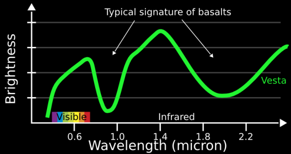

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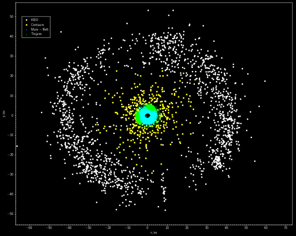
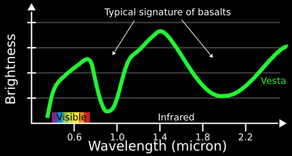
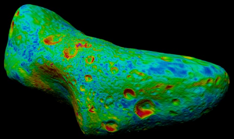
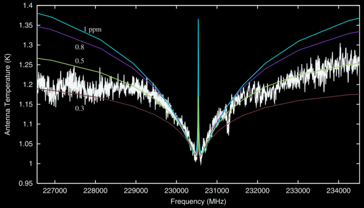




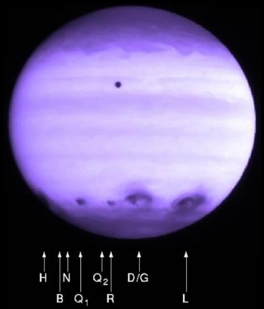


Composition of atmospheres

- Giant planet formation
  - Minor species abundances
  - Sink and sources?
- Atmosphere evolution
  - Surface/Atmosphere interactions
  - Clouds and hazes
- Atmosphere structure
  - Temperature/Pressure
  - Cloud structure
  - Comparative planetology
- METIS/HIRES/HARMONI



Lellouch et al. 2005



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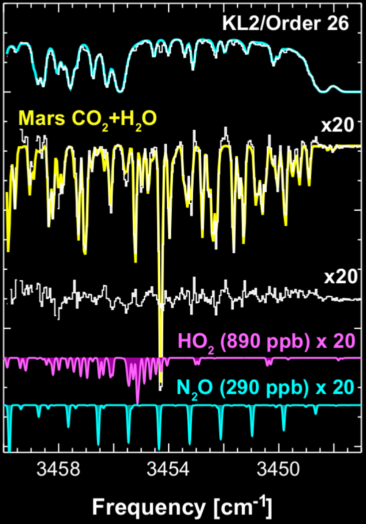
  - High resolution (R≈100k)
  - Spectro-imaging in V+NIR
  - V-MidIR: NACO/CRIRES/VISIR



Villanueva et al. 2013

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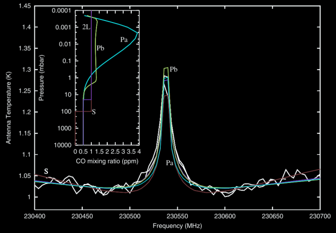
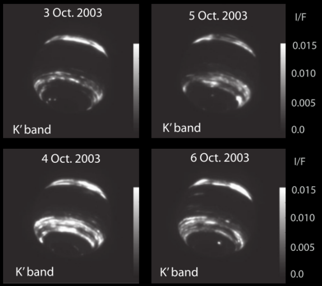


Adapted from Lellouch et al. 2005



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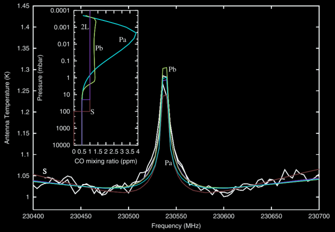

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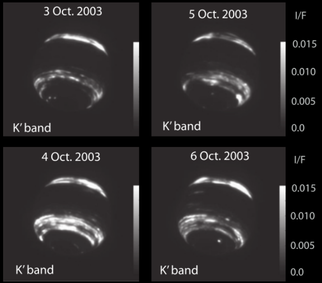

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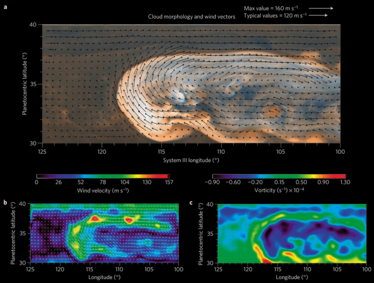
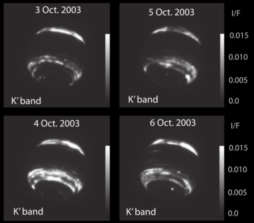
Dynamics of atmospheres



García-Melendo et al. 2013



de Pater et al. 2014

- **Atmosphere structure**
  - Winds & Streams
  - Global circulation
- **Atmosphere evolution**
  - Chemistry $\leftrightarrow$ Dynamics
  - Condensation
  - Evaporation
- **Long-term monitoring**
  - Post-Cassini?
  - Neptune & Uranus
- **METIS/HIRES/HARMONI**
  - High resolution (R$\approx$100k)
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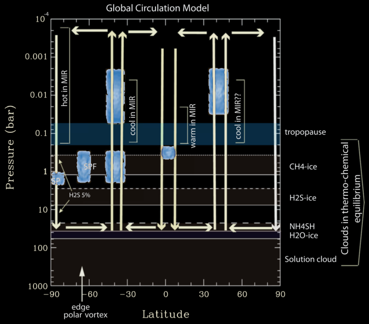

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5. **Satellites & rings**
   - Formation of large satellites
   - Capture of irregular satellite
   - Dynamics of rings

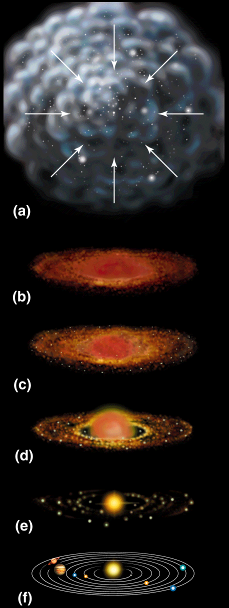
Giant planet systems

1. Classical satellites: equatorial, large
   - In-situ formation early in the Solar System
   - Small *icy* planets, with internal energy
   - Tracers of host planets close environment
   - ▸ Mini-solar system laboratory

2. Irregular satellites: inclined, small
   - Captured during late planetary instability
   - Tracers of host planets surroundings
   - ▸ Another constraint for formation/evolution models

3. Equatorial rings

Formation of satellites



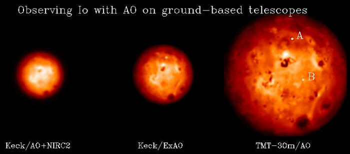
- Canonical scenario
  1. Accretion link in Solar System
  2. Rings from disrupted satellite

- Tides and internal energy
  - Tides deformation
  - Activity in Io, Enceladus
  - Orbital drift
  - Dissipation factor?

- Monitoring MICADO/HARMONI
  - Large: 1–2″
  - Spacecraft limited in time
  - Long-term activity
  - Link with orbits

Formation of satellites

NASA/JPL/Cassini



Courtesy F. Marchis

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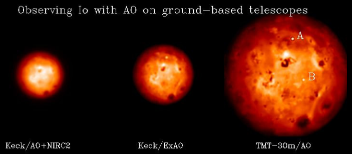

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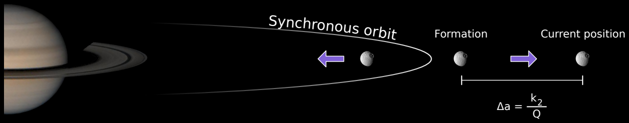
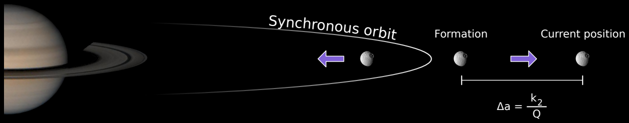


- Satellites are 4.5 Gyrs old
  1. Lower bound on dissipation
  2. Using Mimas: $Q \approx 16{,}000$
- Satellite ephemeris
  - N-body interaction
  - Extended gravity field
  - Tides (inc. Q)
  - Relativity
  - $Q = 1682 \pm 540$

Formation of satellites



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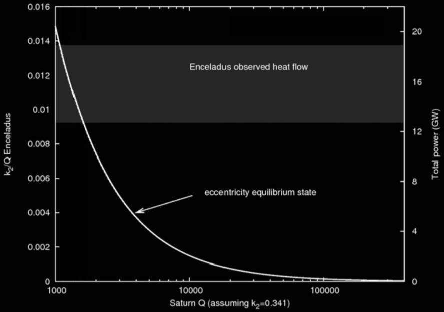
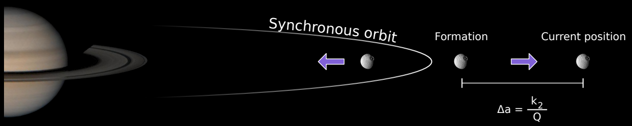


Lainey et al. 2012

Formation of satellites



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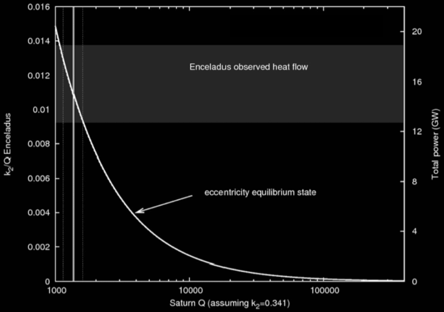

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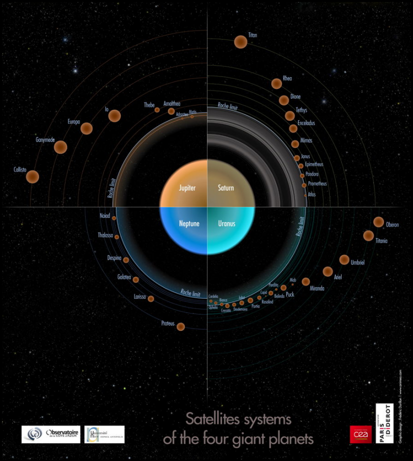
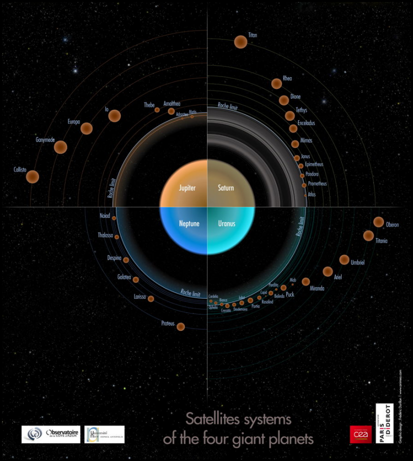
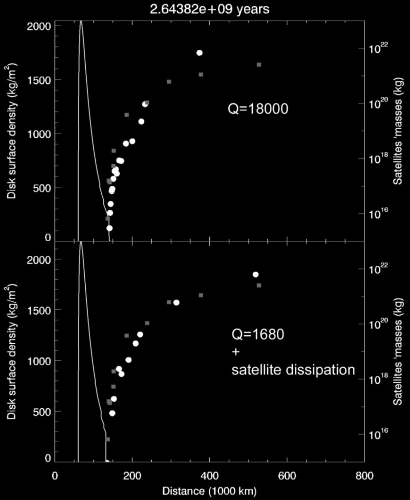


Crida & Charnoz 2012

Formation of satellites



Crida & Charnoz 2012



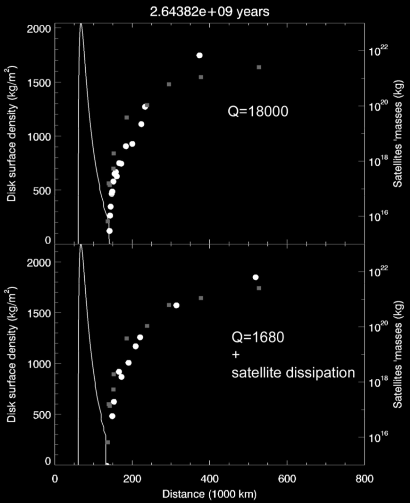
Charnoz et al. 2011

Formation of satellites

A new formation scenario:

1. Massive initial disk
2. Disk spreads viscously
3. Disk crosses the Roche limit
4. Formation of moons
5. Expansion of moon orbits
    - Ring torque
    - Saturn dissipation

- Strong dissipation required
- Post-Cassini?
- Neptune? Uranus?



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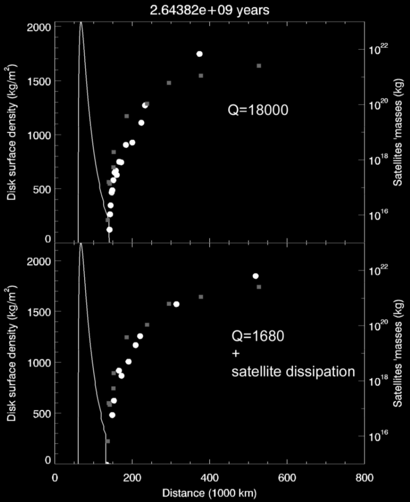

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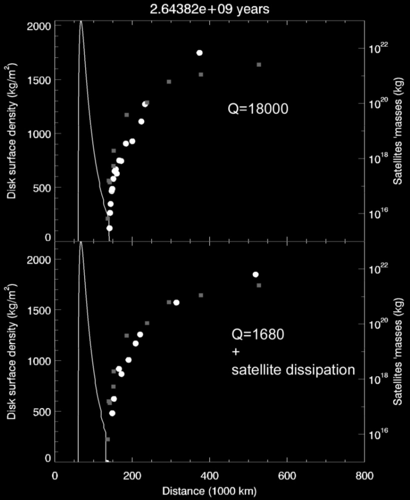

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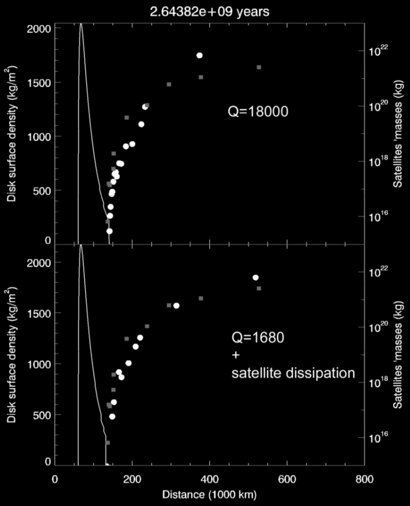
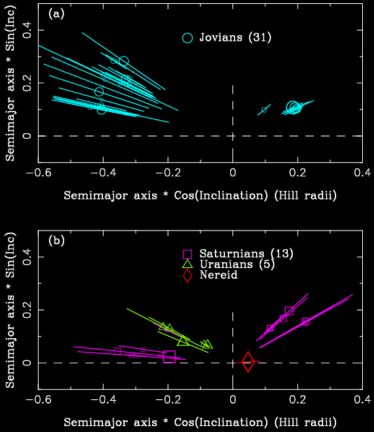


Charnoz et al. 2011

Capture of irregular satellites



Courtesy D. Nesvorny

- Irregular satellites
  - High inclination
  - Peculiar SFD
- Captured in planetary instability
  - Constrains for Nice model
  - SFD & **composition**
  - Original material $\in$ [5-30] au
- Targets for LSST/HARMONI
  - Survey $\rightarrow$ LSST
  - Spectra in V+NIR
  - $V \geq 22$

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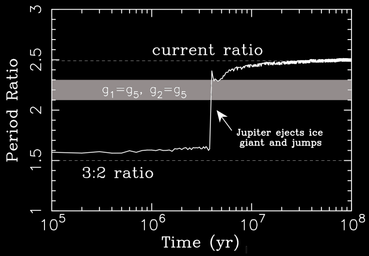

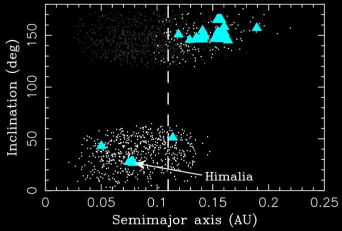

Nesvorny et al. 2014

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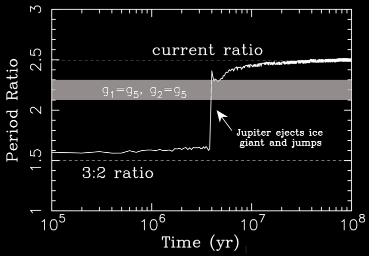

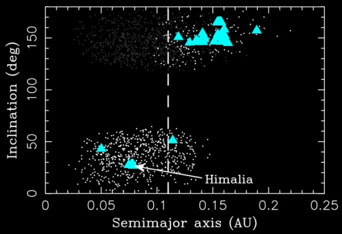

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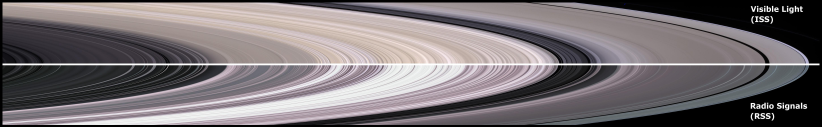
Dynamics of rings



NASA/JPL/Cassini

- Ring formation?
- Interaction with satellites?
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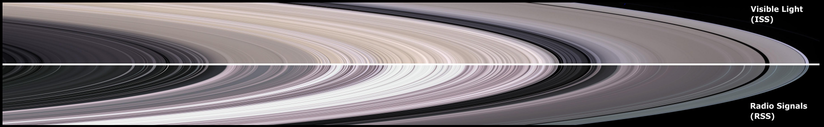
Dynamics of rings



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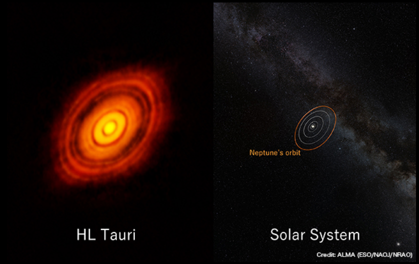
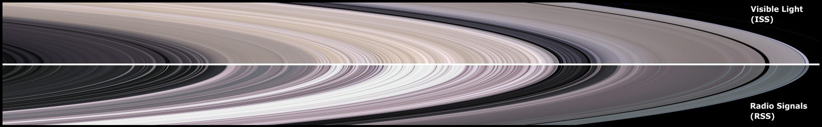


ALMA (ESO/NAOJ/NRAO)

Dynamics of rings



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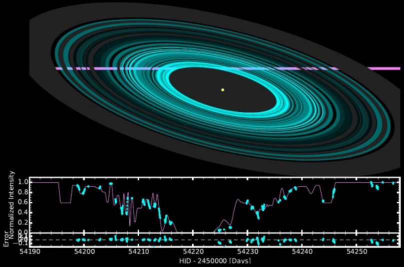
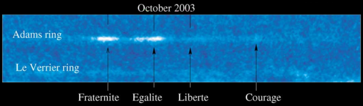


Kenworthy & Mamajek 2015

Ring-Satellite Interaction

NASA/Voyager



de Pater et al. 2005

- Structure are not stable alone
  - Destroyed by keplerian shear
  - Lifetime < year
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  - Cleaning via accretion
  - Shepherding via attraction
- Targets for MICADO/HARMONI
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  - Structures ∈ 0.15-0.6″
  - Close to Neptune: 1–2″
  - Neptune V-K: 8→12
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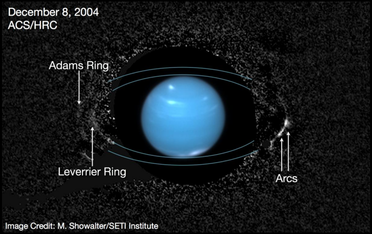
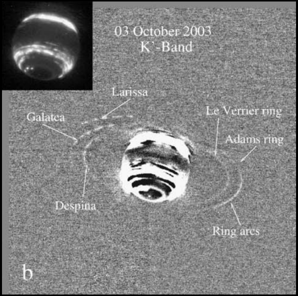


Showalter et al. HST/PR



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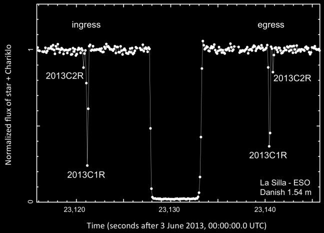

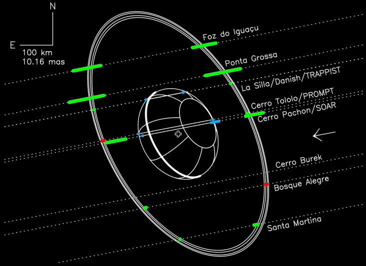

Bragas-Ribas et al. 2014

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