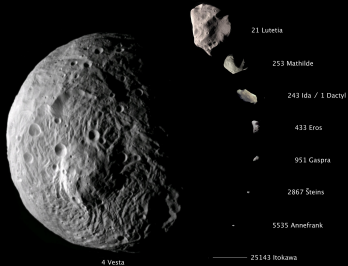


Solar system science in the E-ELT era



B. Carry^{1,2}

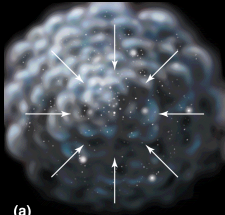
¹IMCCE, Observatoire de Paris

²Lagrange, Observatoire de la Côte d'Azur

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

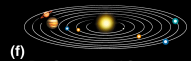
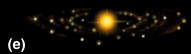
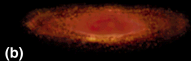
1. Planetary formation
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Planetary formation: Sketch

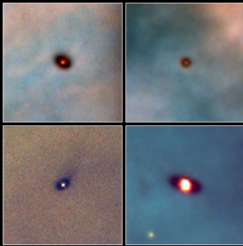


A step-by-step process:

- 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



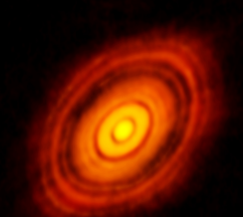
Planetary formation: Examples



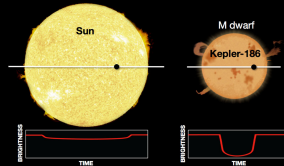
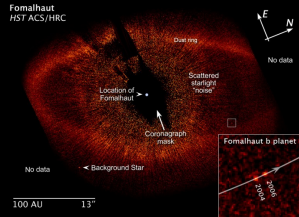
Protoplanetary Disks
Orion Nebula

HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



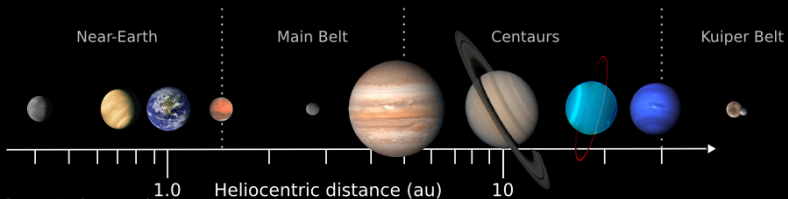
ALMA (ESO/NAOJ/NRAO)



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

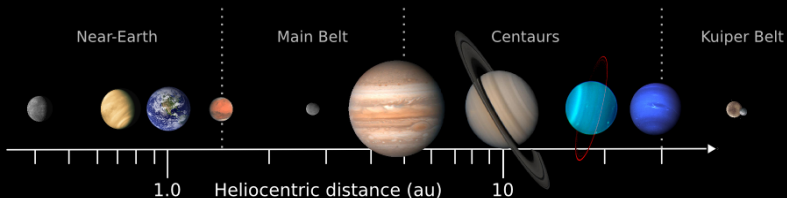
1. Large population

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

2. Primitive population

- **Small** objects [m $\rightarrow$ 10^3 km]
- Internal energy $\approx$ null
- No endogeneous activity

▷ *Direct* witnesses of the early Solar System



1. Planetary formation

2. Solar system history

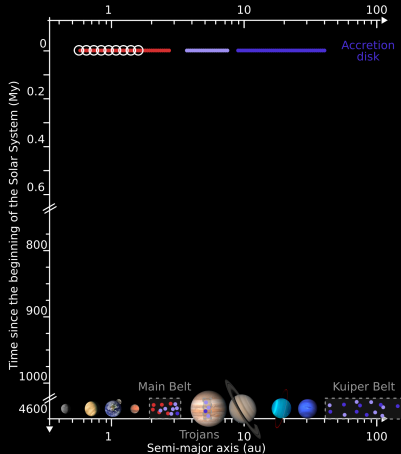
- ▷ Observational evidences
- ▷ Early event: the Grand Tack
- ▷ Late planetary instability: the Nice model

3. Open questions

4. Planets

5. Satellites & rings

History: Evidences



DeMeo & Carry 2014

A. Accretion disk

- Gas & Dust
- Composition gradient

B. Planets

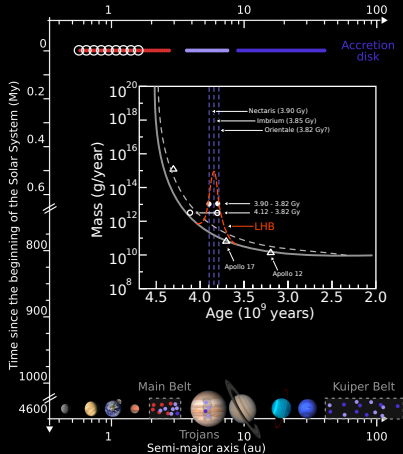
- Relative masses
- Eccentricities
- Compositions

C. Small bodies

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

D. Late Heavy Bombardment

History: Evidences



DeMeo & Carry 2014

A. Accretion disk

- Gas & Dust
- Composition gradient

B. Planets

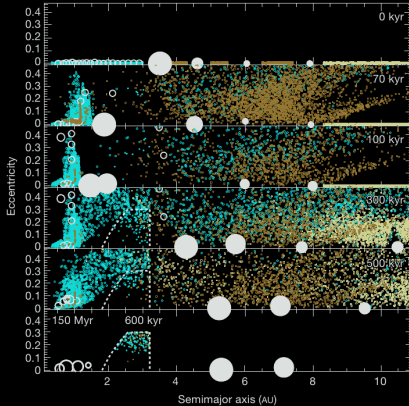
- Relative masses
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C. Small bodies

- Belts mass & SFD
- Mixed asteroids
- Homogeneous Trojans
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D. Late Heavy Bombardment

History: Gran Tack



Walsh et al. 2011

A. Jupiter moves inward

- Bowling strike
- ▶ Mass of Mars
- ▶ Deplete MB

B. Jupiter moves outward

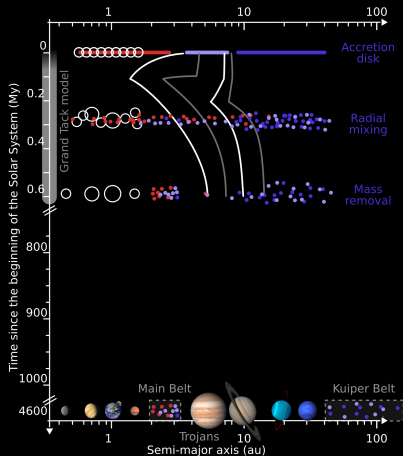
- Excite orbits
- Mix inner → MB

C. Result for **Inner** Solar System

- Complete mixing
- Removal of 99% mass



History: Gran Tack



DeMeo & Carry 2014

A. Jupiter moves inward

- Bowling strike
- ▶ Mass of Mars
- ▶ Deplete MB

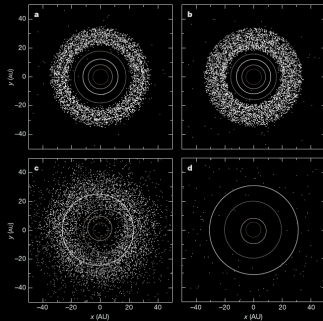
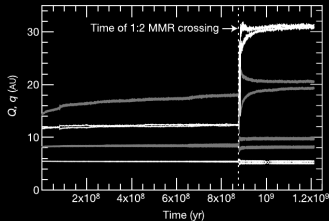
B. Jupiter moves outward

- Excite orbits
- Mix inner → MB

C. Result for **Inner** Solar System

- Complete mixing
- Removal of 99% mass

History: Nice



Gomes/Tsiganis/Morbidelli 2005

A. Original idea

- Smooth migration
- Jupiter-Saturn resonance

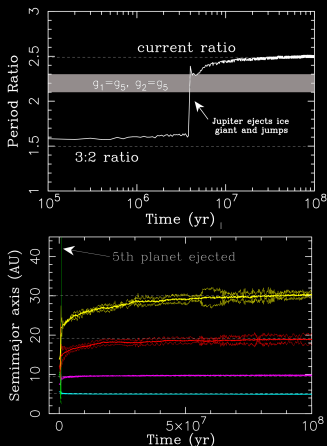
B. New paradigm

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

C. Results for Solar System

- Mix outer $\rightarrow$ MB
- Trojans replaced
- Satellite captured
- Fifth or sixth giant planet!

History: Nice



Morbidelli et al. 2007/2010+

Nesvorny/Batygin 2011/2012

A. Original idea

- Smooth migration
- Jupiter-Saturn resonance

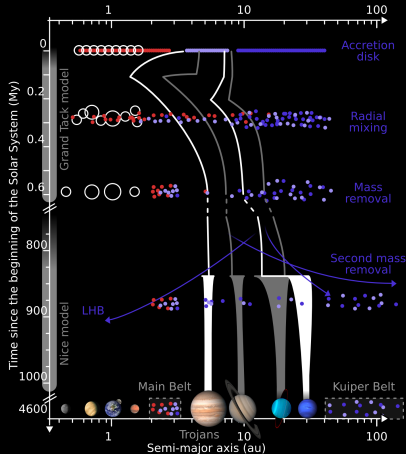
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History: Nice



DeMeo & Carry 2014

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- Smooth migration
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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!

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

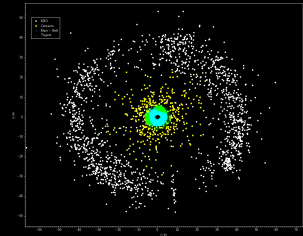
2. Dynamics: Short & Long-Term

- Numerical simulation
- Analytical

3. Composition

- Laboratory experiments
- Observations: spectroscopy, photometry
- Remote sensing

4. Physical properties



Answers?

1. Discovery & Census

- Observation → population
- New categories of objects
- ▶ Surveys

2. Dynamics: Short & Long-Term

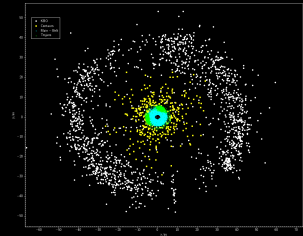
- Origin & evolution
- ▶ Astrometry

3. Composition

- Asteroids, comets, Kuiper belt objects
- Planets, moons, rings
- Atmospheres, oceans, clouds
- Planetary interiors

4. Physical properties

- Surface, clouds, winds
- Gravity, magnetic fields
- Rotation, obliquity
- Tidal forces



Answers?

1. Discovery & Census

- Observation → population
- New categories of objects
- ▶ Surveys

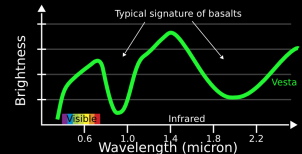
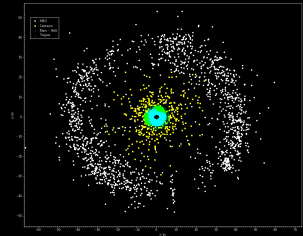
2. Dynamics: Short & Long-Term

- Origin & evolution
- ▶ Astrometry

3. Composition

- Asteroids/Meteors → Mineralogy
- Comets/KBOs → Volatiles
- ▶ Spectrometry

4. Physical properties



Answers?

1. Discovery & Census

- Observation → population
- New categories of objects
- ▶ Surveys

2. Dynamics: Short & Long-Term

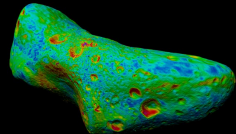
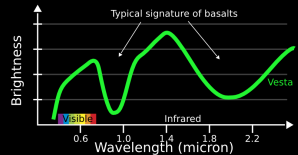
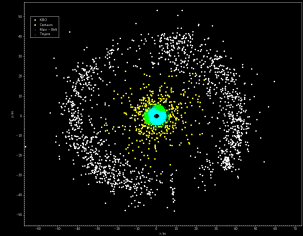
- Origin & evolution
- ▶ Astrometry

3. Composition

- Asteroids/Meteors → Mineralogy
- Comets/KBOs → Volatiles
- ▶ Spectrometry

4. Physical properties

- Starlike → Worlds
- Structure: interior & surface
- ▶ Imaging



1. Planetary formation
2. Solar system history
3. Open questions
4. **Planets**
 - ▷ Composition of atmospheres
 - ▷ Dynamics of atmospheres
5. Satellites & rings

Composition of atmospheres

► Giant planet formation

- Minor species abundances
- Sink and sources?

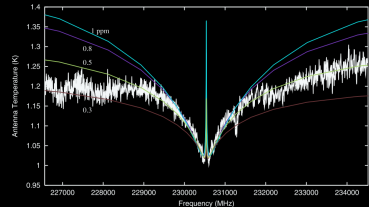
► Atmosphere evolution

- Evolution of atmospheric composition with time
- Clouds and hazes

► Atmosphere structure

- Temperature, pressure, wind structure
- Cloud structure
- Chemical structure

► METIS/HIRES/HARMONI



Lellouch et al. 2005



Composition of atmospheres

► Giant planet formation

- Minor species abundances
- Sink and sources?

► Atmosphere evolution

- Surface/Atmosphere interactions
- Clouds and hazes

► Atmosphere structure

- Temperature profile
- Density profile
- Wind profile

► Atmospheric dynamics

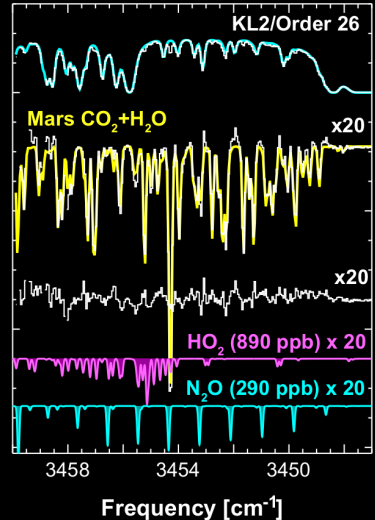
- Clouds and hazes
- Winds and storms
- Aerosols

► Atmospheric chemistry

- Photochemistry
- Aerosols
- Clouds and hazes

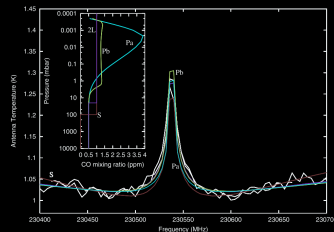
► METIS/HIRES/HARMONI

- Spectroscopy
- Imaging
- Polarimetry

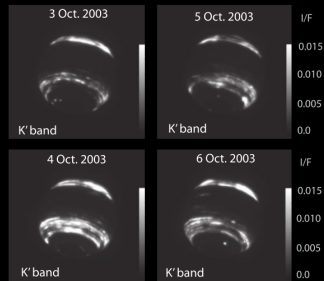


Composition of atmospheres

- ▶ 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



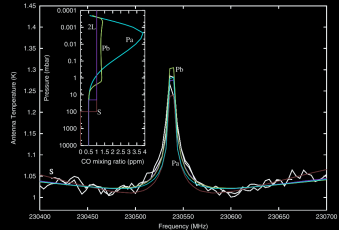
Adapted from Lellouch et al. 2005



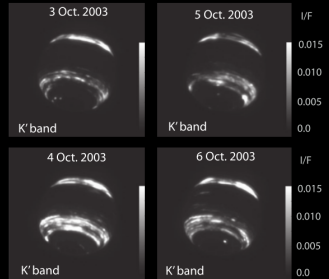
Adapted from de Pater et al. 2014

Composition of atmospheres

- ▶ Giant planet formation
 - Minor species abundances
 - Sink and sources?
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 - Surface/Atmosphere interactions
 - Clouds and hazes
- ▶ Atmosphere structure
 - Temperature/Pressure
 - Cloud structure
 - Comparative planetology
- ▶ METIS/HIRES/HARMONI
 - High resolution ($R \approx 100k$)
 - Spectro-imaging in V+NIR
 - V-MidIR: NACO/CRIRES/VISIR

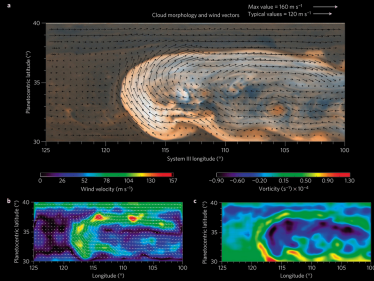


Adapted from Lellouch et al. 2005

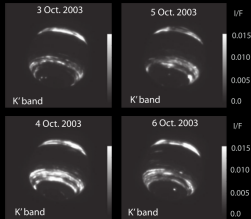


Adapted from de Pater et al. 2014

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

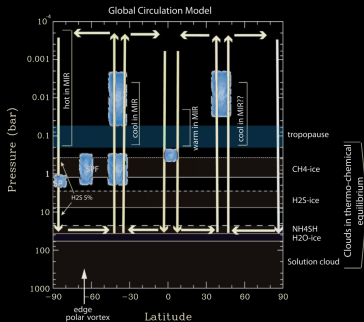
► Long-term monitoring

- Post-Cassini?
- Neptune & Uranus

► METIS/HIRES/HARMONI

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

Dynamics of atmospheres



de Pater et al. 2014

► Atmosphere structure

- Winds & Streams
- Global circulation

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- Chemistry ↔ Dynamics
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- Evaporation

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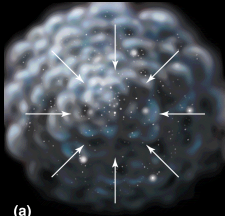
1. Planetary formation
2. Solar system history
3. Open questions
4. Planets
5. Satellites & rings
 - ▷ Formation of large satellites
 - ▷ Capture of irregular satellite
 - ▷ Dynamics of rings

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

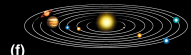
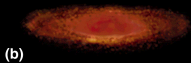
1. Accretion link in Solar System
2. Rings from disrupted satellite

► Tides and internal energy

- Tides deformation
- Accretion in the protoplanet
- Disruption of the protoplanet
- Formation of rings

► Monitoring MICADO/HARMONI

- High resolution
- Spectroscopy (doppler effect)
- Long term monitoring
- High contrast



Formation of satellites



NASA/JPL/Cassini

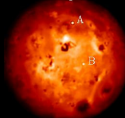
Observing Io with AO on ground-based telescopes



Keck/AO+NIRC2



Keck/ExAO



TMT-30m/AO

Courtesy F. Marchis

► 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

- MICADO/HARMONI will be able to observe the surface of the Galilean satellites
- MICADO/HARMONI will be able to observe the surface of the Galilean satellites
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Formation of satellites



NASA/JPL/Cassini

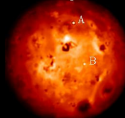
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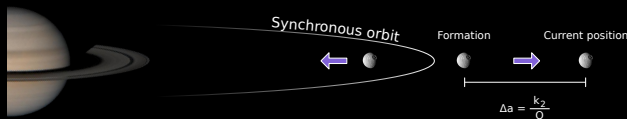
► Tides and internal energy

- 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



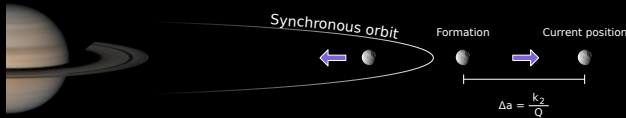
► Satellites are 4.5 Gyrs old

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

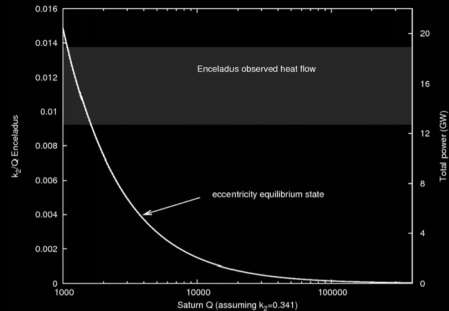


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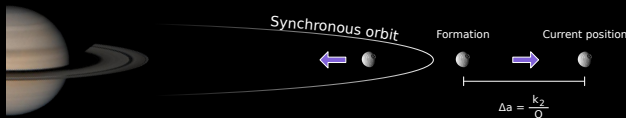
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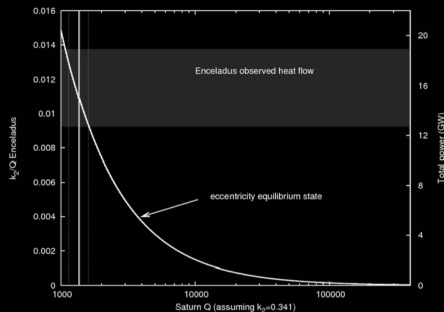


Lainey et al. 2012

Formation of satellites

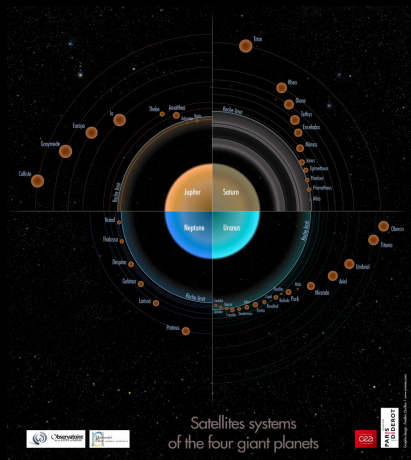


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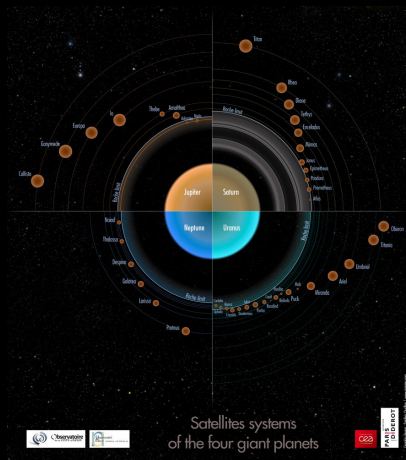
Lainey et al. 2012

Formation of satellites

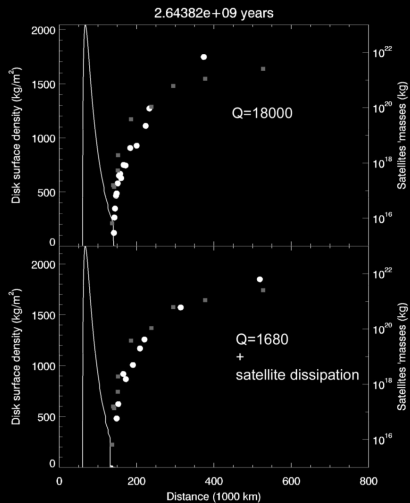


Crida & Charnoz 2012

Formation of satellites



Crida & Charnoz 2012



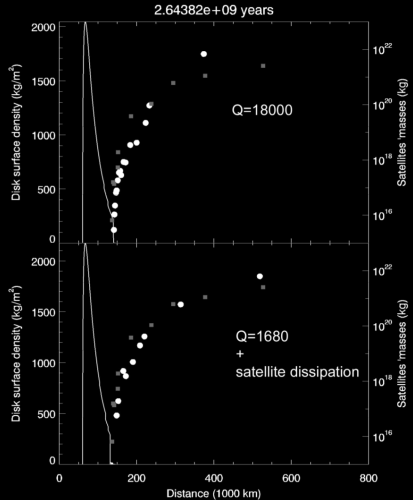
Charnoz et al. 2011

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?



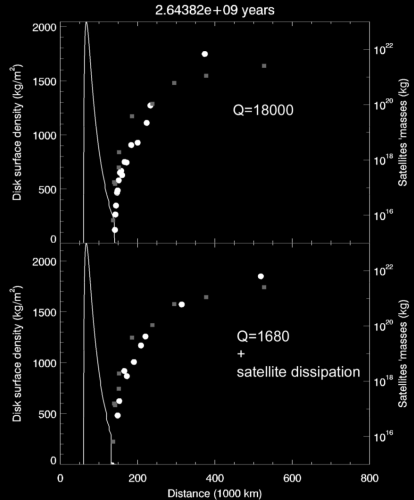
Charnoz et al. 2011

Formation of satellites

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 - Ring torque
 - Saturn dissipation

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



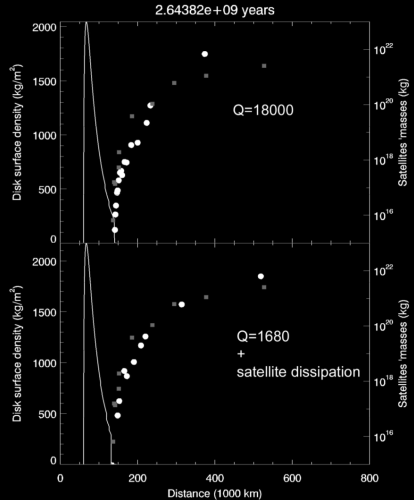
Charnoz et al. 2011

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?

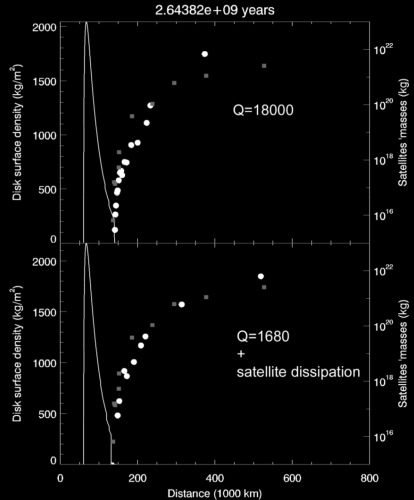


Charnoz et al. 2011

Formation of satellites

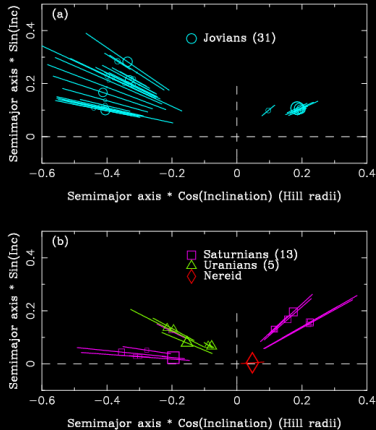
A new formation scenario:

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Charnoz et al. 2011

Capture of irregular satellites



► Irregular satellites

- High inclination
- Peculiar SFD

► Captured in planetary instability

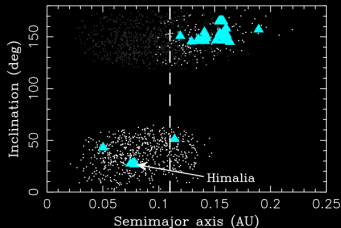
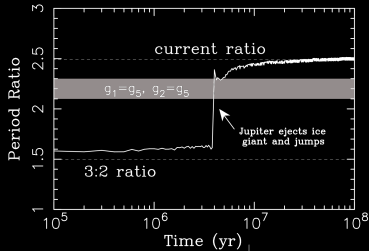
- Consistent with the model of capture of comets
- Similar composition to interstellar material
- Consistent with capture of interstellar material

► Targets for LSST/HARMONI

- 1000000+ LSST
- 1000000+ HARMONI

Courtesy D. Nesvorný

Capture of irregular satellites



Nesvorný et al. 2014

► Irregular satellites

- High inclination
- Peculiar SFD

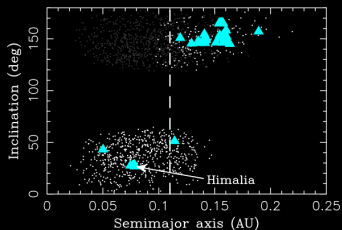
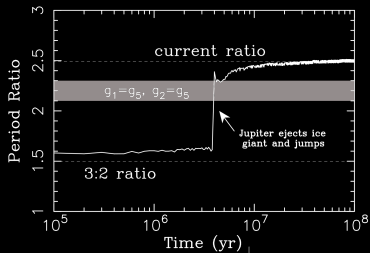
► Captured in planetary instability

- Constrains for Nice model
- SFD & **composition**
- Original material $\in [5-30]$ au

► Targets for LSST/HARMONI

- $\sim 10^4$ objects
- $\sim 10^4$ objects

Capture of irregular satellites



Nesvorný et al. 2014

► Irregular satellites

- High inclination
- Peculiar SFD

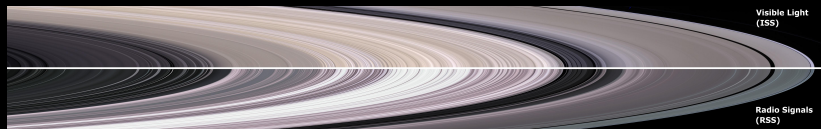
► Captured in planetary instability

- Constrains for Nice model
- SFD & **composition**
- Original material $\in [5-30]$ au

► Targets for LSST/HARMONI

- Survey $\rightarrow$ LSST
- Spectra in V+NIR
- $V \geq 22$

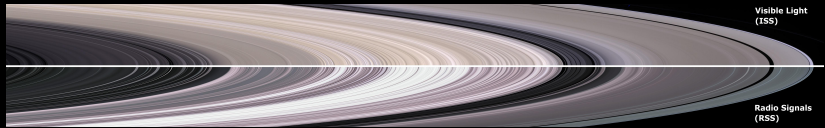
Dynamics of rings



NASA/JPL/Cassini

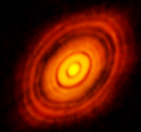
- Ring formation?
- Interaction with satellites?
- Long-term stability?
- Laboratory for accretion disks

Dynamics of rings



NASA/JPL/Cassini

- Ring formation?
- Interaction with satellites?
- Long-term stability?
- Laboratory for accretion disks



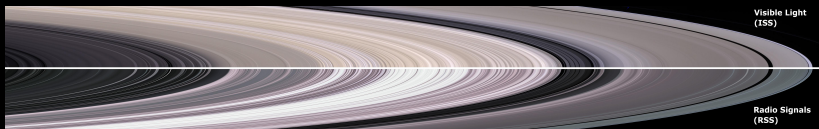
HL Tauri



Credit: ALMA (ESO/NAOJ/NRAO)

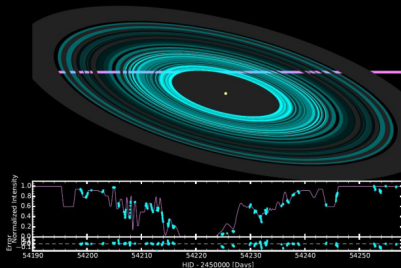
ALMA (ESO/NAOJ/NRAO)

Dynamics of rings



NASA/JPL/Cassini

- Ring formation?
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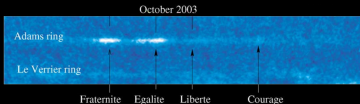


Kenworthy & Mamajek 2015

Ring-Satellite Interaction



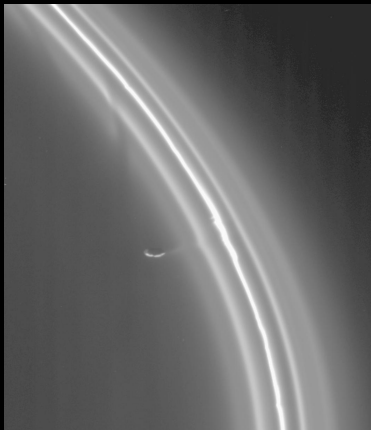
NASA/Voyager



de Pater et al. 2005

- ▶ Structure are not stable alone
 - Destroyed by keplerian shear
 - Lifetime < year
- ▶ Interaction with satellites
 - $\omega_{\text{ring}} \neq \omega_{\text{satellite}}$
 - $\omega_{\text{ring}} \neq \omega_{\text{planet}}$
- ▶ Targets for MICADO/HARMONI
 - $\omega_{\text{ring}} \neq \omega_{\text{planet}}$
 - $\omega_{\text{ring}} \neq \omega_{\text{satellite}}$
 - $\omega_{\text{ring}} \neq \omega_{\text{planet}}$
 - $\omega_{\text{ring}} \neq \omega_{\text{satellite}}$
- ▶ More ring surprises

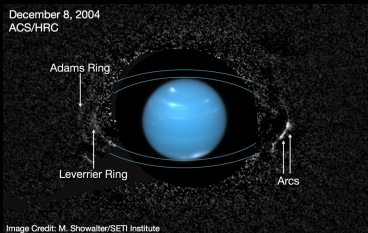
Ring-Satellite Interaction



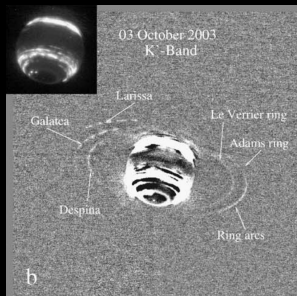
NASA/JPL/Cassini

- ▶ Structure are not stable alone
 - Destroyed by keplerian shear
 - Lifetime < year
- ▶ Interaction with satellites
 - Cleaning via accretion
 - Shepherding via attraction
- ▶ Targets for MICADO/HARMONI
 - Cassini's last orbits will be close to the rings
 - Cassini's last orbits will be close to the rings
 - Cassini's last orbits will be close to the rings
 - Cassini's last orbits will be close to the rings
 - Cassini's last orbits will be close to the rings
- ▶ More ring surprises
 - New rings around Charon
 - New rings around Uranus
 - New rings around Neptune
 - New rings around Pluto

Ring-Satellite Interaction



Showalter et al. HST/PR



de Pater et al. 2005

► Structure are not stable alone

- Destroyed by keplerian shear
- Lifetime < year

► Interaction with satellites

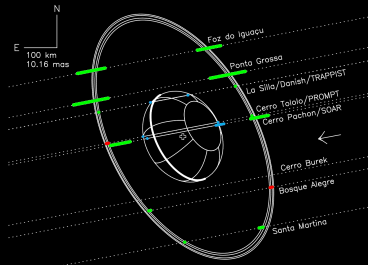
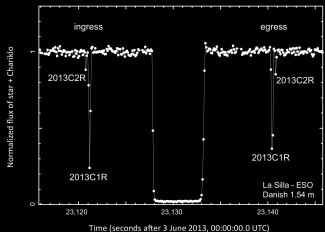
- Cleaning via accretion
- Shepherding via attraction

► Targets for MICADO/HARMONI

- Ring/Satellites @ $V \approx 20-25+$
- Structures $\in 0.15-0.6''$
- Close to Neptune: $1-2''$
- Neptune V-K: $8 \rightarrow 12$

► More ring surprises

Ring-Satellite Interaction



Bragas-Ribas et al. 2014

- ▶ Structure are not stable alone
 - Destroyed by keplerian shear
 - Lifetime < year
- ▶ Interaction with satellites
 - Cleaning via accretion
 - Shepherding via attraction
- ▶ Targets for MICADO/HARMONI
 - Ring/Satellites @ $V \approx 20-25+$
 - Structures $\in 0.15-0.6''$
 - Close to Neptune: $1-2''$
 - Neptune V-K: $8 \rightarrow 12$
- ▶ More ring surprises
 - Two rings around Chariklo
 - Chiron? Others?
 - ▶ Non-spherical central body