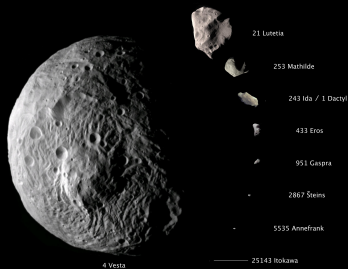


L'histoire du système solaire vue par les petits corps

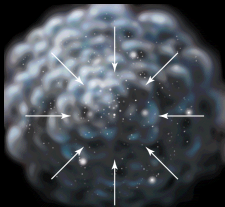


B. Carry^{1,2}

¹IMCCE, Observatoire de Paris

²Lagrange, Observatoire de la Côte d'Azur

Formation planétaire: Résumé



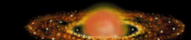
(a)



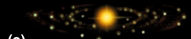
(b)



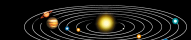
(c)



(d)



(e)

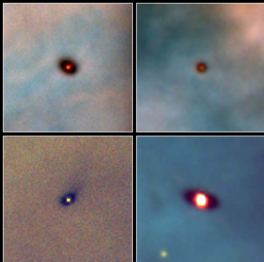


(f)

Un processus par étapes successives:

- a. Contraction du nuage de gaz & poussière
- b. Formation d'un disque
- c. Rotation, accumulation de matériaux
- d. Naissance de l'étoile
- e. Accrétion dans le disque et planétésimaux
- f. Système planétaire

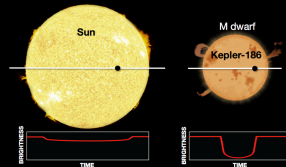
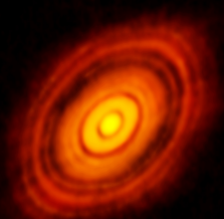
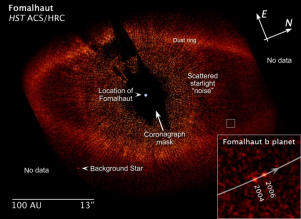
Formation planétaire: Exemples



Protoplanetary Disks
Orion Nebula

HST · WFPC2

PRC95-15b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



Formation planétaire: Petits corps

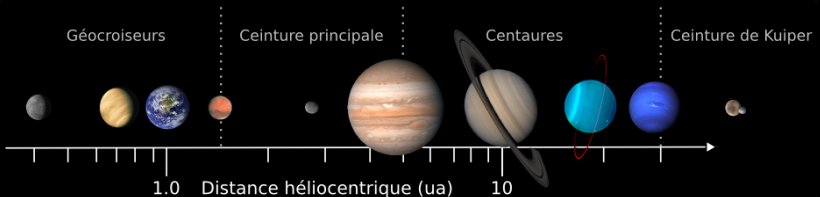
1. Population **importante**

- 700 000 objets (*plusieurs millions*)
- Large gamme de compositions [roches → glaces]
- Large gamme de distances héliocentriques [$1 \rightarrow 10^{2-5}$ ua]

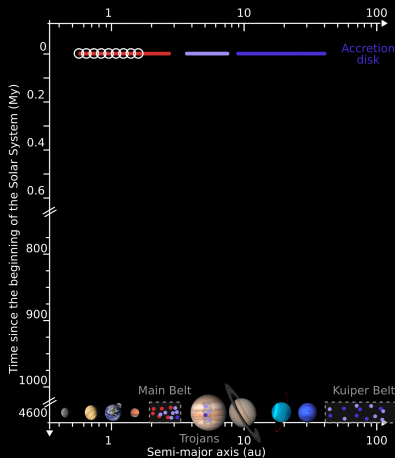
2. Population **primitive**

- **Petits** objets [m → 10^3 km]
- Énergie interne \approx nulle
- Pas d'activité endogène

▷ Témoins *directs* du jeune Système Solaire



Histoire: Preuves



DeMeo & Carry 2014

A. Disque d'accrétion

- Gaz & Poussière
- Gradient de composition

B. Planètes

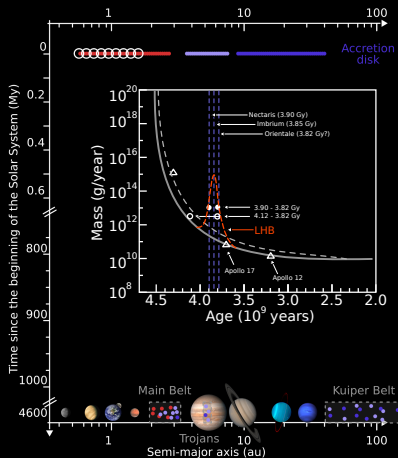
- Masses relatives
- Excentricités
- Compositions

C. Petits corps

- Masse des ceintures
- Mixité des astéroïdes
- Homogénéité des troyens
- Inclinaison des TNOs

D. Bombardement tardif

Histoire: Preuves



DeMeo & Carry 2014

A. Disque d'accrétion

- Gaz & Poussière
- Gradient de composition

B. Planètes

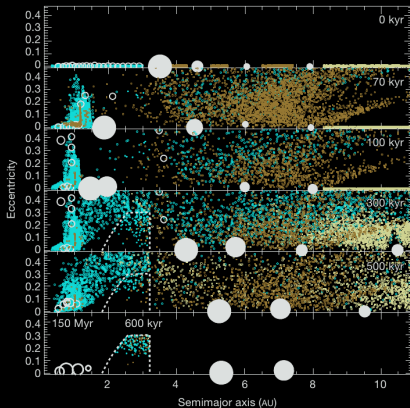
- Masses relatives
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- Masse des ceintures
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Histoire: le "Grand Tack"



Walsh et al. 2011

A. Jupiter migre vers l'intérieur

- Explique la masse de Mars
- Diminue la ceinture principale

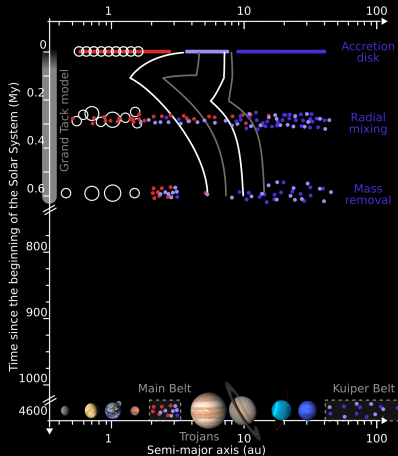
B. Jupiter migre vers l'extérieur

- Excite les orbites
- Mélange les parties internes

C. Bilan

- Mélange complet
- Perte de 99% de la masse

Histoire: le "Grand Tack"



DeMeo & Carry 2014

A. Jupiter migre vers l'intérieur

- Explique la masse de Mars
- Diminue la ceinture principale

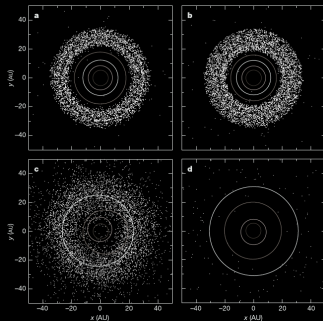
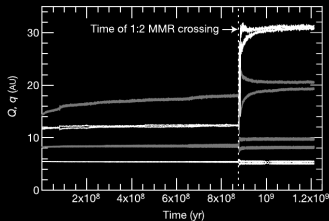
B. Jupiter migre vers l'extérieur

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- Mélange les parties internes

C. Bilan

- Mélange complet
- Perte de 99% de la masse

Histoire: Modèle de Nice



Gomes/Tsiganis/Morbidelli 2005

A. Idée originelle

- Migration douce
- Résonance Jupiter-Saturne

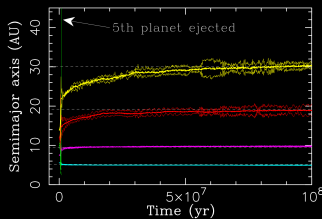
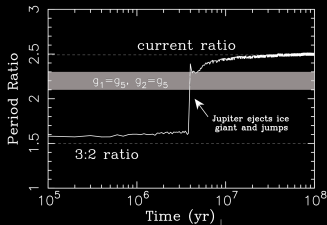
B. Nouveau paradigme

- Géante glacée
- **Jumping** Jupiter

C. Bilan

- Mélange complet
- Troyens remplacés
- Satellites capturés
- ▶ 5 ou 6 planètes géantes!

Histoire: Modèle de Nice



A. Idée originelle

- Migration douce
- Résonance Jupiter-Saturne

B. Nouveau paradigme

- Géante glacée
- **Jumping Jupiter**

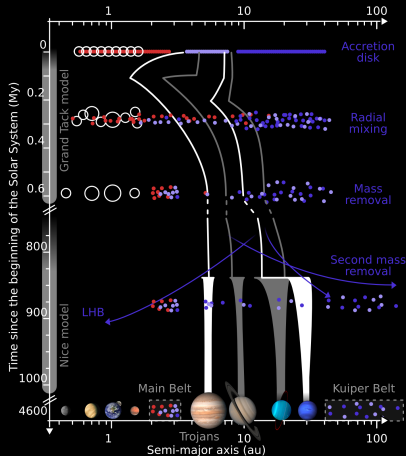
C. Bilan

- Mélange complet
- Troyens remplacés
- Satellites capturés
- ▶ **5 ou 6 planètes géantes!**

Morbidelli et al. 2007/2010+

Nesvorny/Batygin 2011/2012

Histoire: Modèle de Nice



DeMeo & Carry 2014

A. Idée originelle

- Migration douce
- Résonance Jupiter-Saturne

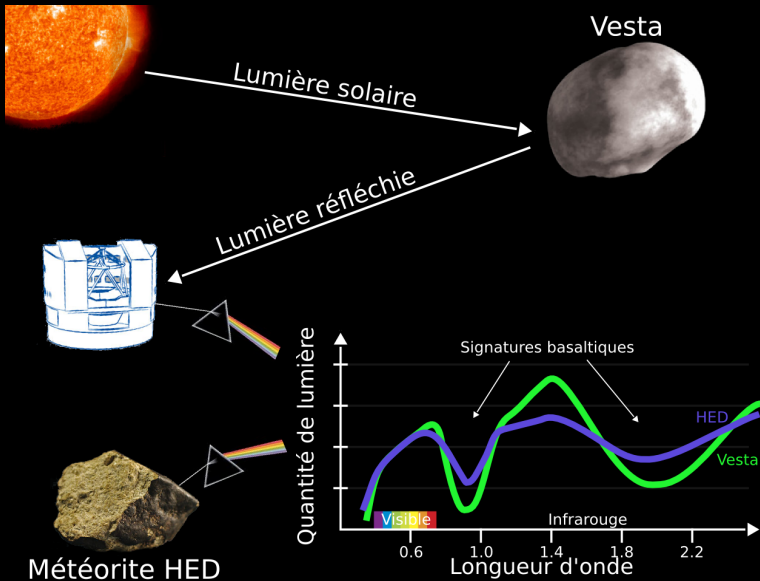
B. Nouveau paradigme

- Géante glacée
- **Jumping Jupiter**

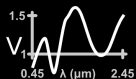
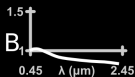
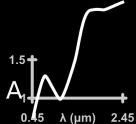
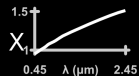
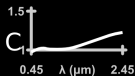
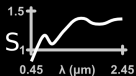
C. Bilan

- Mélange complet
- Troyens remplacés
- Satellites capturés
- ▶ 5 ou 6 planètes géantes!

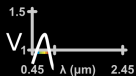
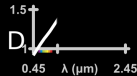
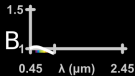
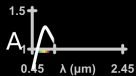
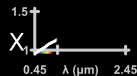
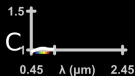
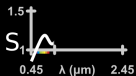
Composition: Spectroscopie



Composition dans le visible

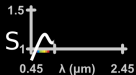


Composition dans le visible

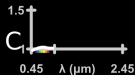


Composition dans le visible

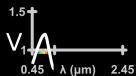
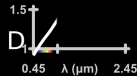
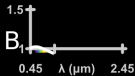
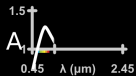
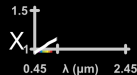
Bande 1 μ m



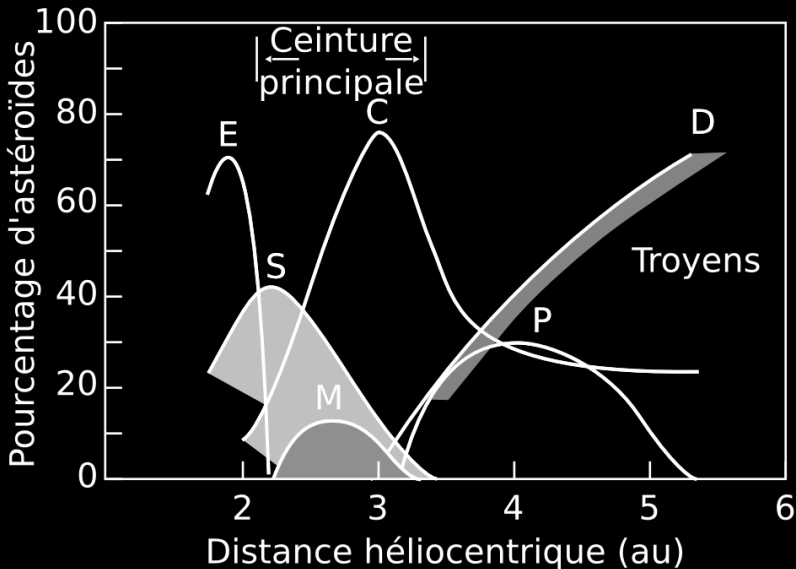
Plat



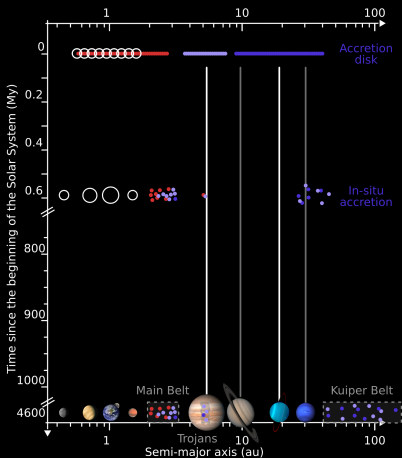
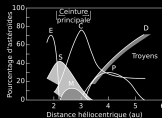
Très rouge



Composition dans le visible

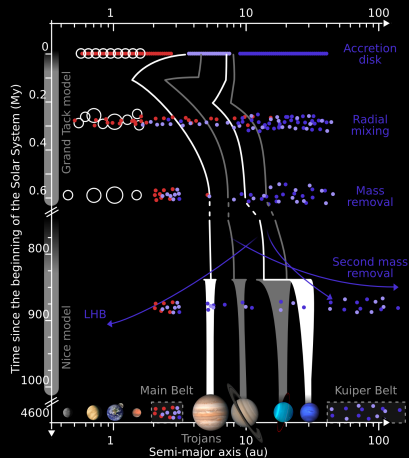
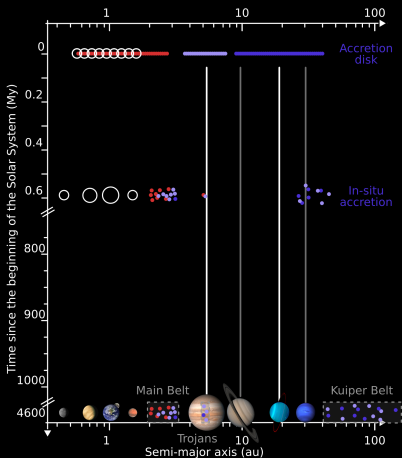
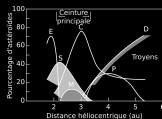


Structure de la ceinture principale





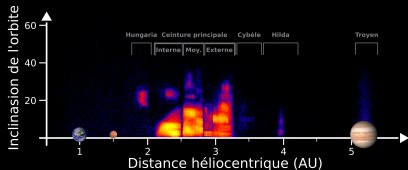
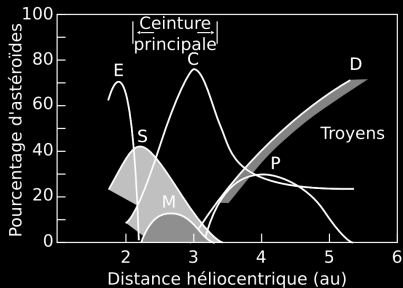
Structure de la ceinture principale



Structure de la ceinture principale

1. Attention aux fractions!

- ▶ Perd la structure
- ▶ Rien entre 3.3–5 AU
- ▶ Hungarias ≠ Ceinture
- ▶ Troyens ≠ Ceinture



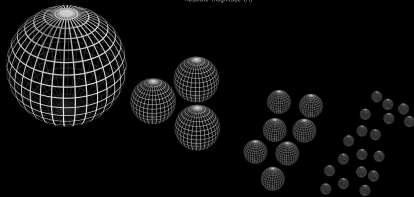
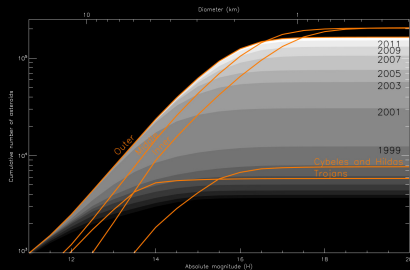
Structure de la ceinture principale

1. Attention aux **fractions**!

- ▶ Perd la structure
- ▶ *Rien* entre 3.3–5 AU
- ▶ Hungarias \neq Ceinture
- ▶ Troyens \neq Ceinture

2. Attention aux **nombres**!

- ▶ Perd les proportions
- ▶ **Un** Cérès @ 1000 km
- ▶ 10^6 astéroïdes @ 1 km
- ▶ **Mais** Cérès = 20% masse



Structure de la ceinture principale

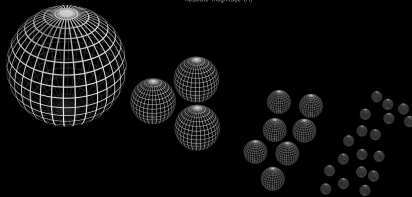
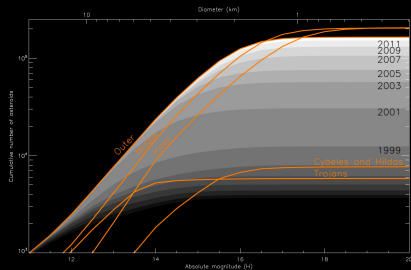
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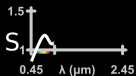
- ▶ Perd les proportions
- ▶ **Un** Cérès @ 1000 km
- ▶ 10^6 astéroïdes @ 1 km
- ▶ **Mais** Cérès = 20% masse

3. Seulement **600 objets**!

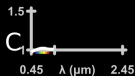


Composition: WETAL2011

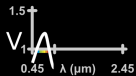
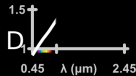
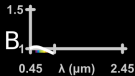
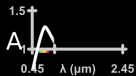
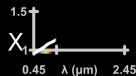
Bande 1 μ m



Plat

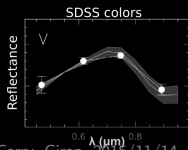
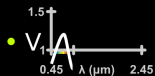
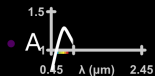
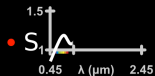


Très rouge

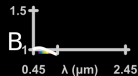
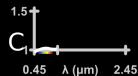


Composition: WETAL2011

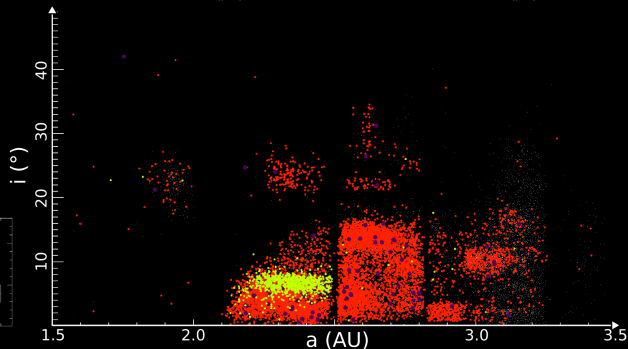
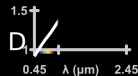
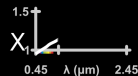
Bande 1 μ m



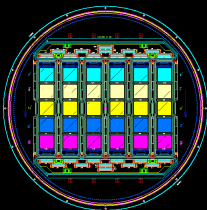
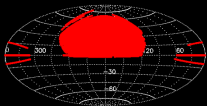
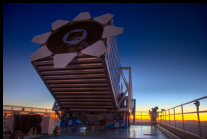
Plat



Très rouge



The Sloan Digital Sky Survey



▶ Large-area sky survey: 1998-2009

- 12,000 degrés carrés
- Pixels de 0.4''
- 400 millions de sources

▶ Photométrie dans le visible

- 5 filtres: ugriz
- Magnitude limite: 22 – 20.5
- Précision @ 2–3%

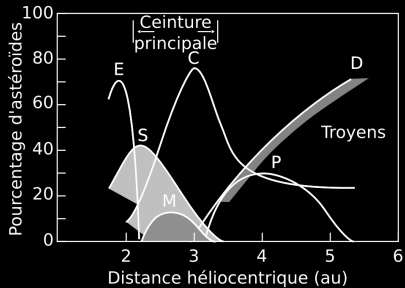
▶ Moving Object Catalog

- 471,569 sources, dont 220,101 reconnues
- 104,449 uniques

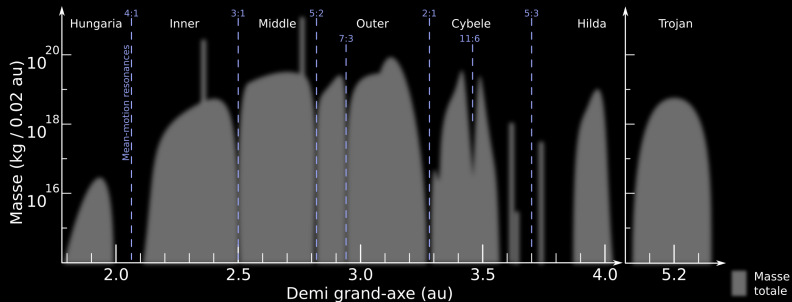
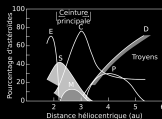
▶ Conjonction incroyable

- Couleurs par SDSS
- Diamètres par WISE
- Densité par Carry2012

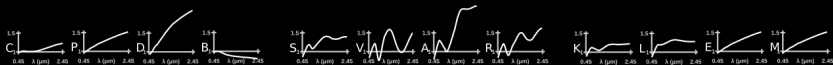
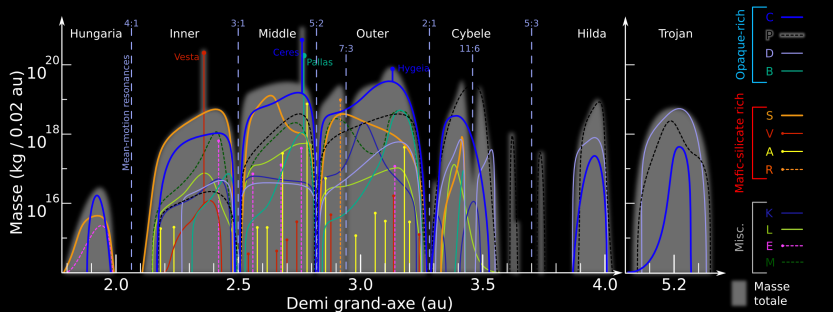
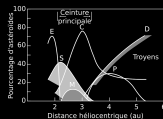
Structure de la ceinture



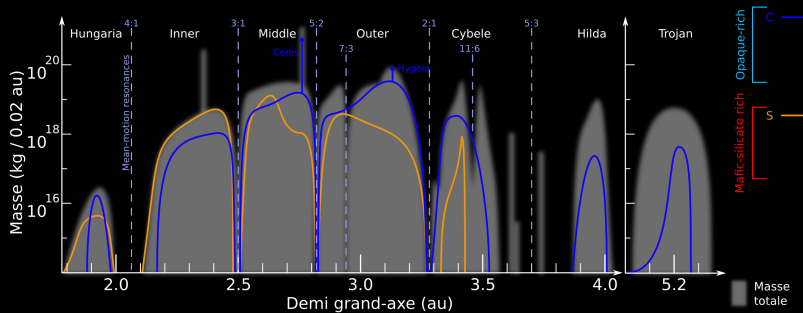
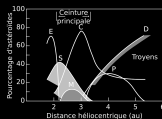
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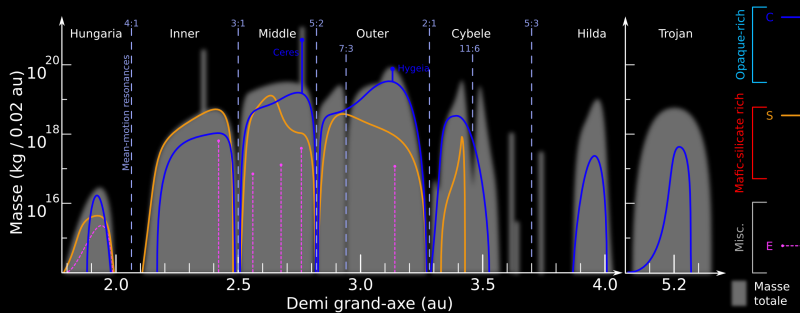
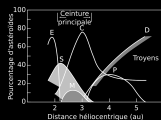
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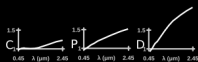
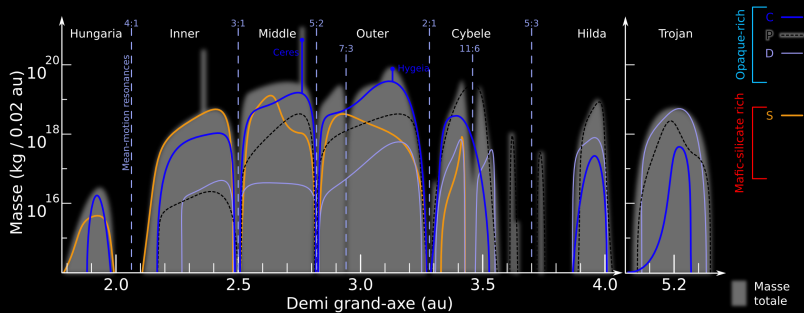
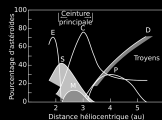
Structure de la ceinture



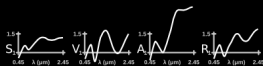
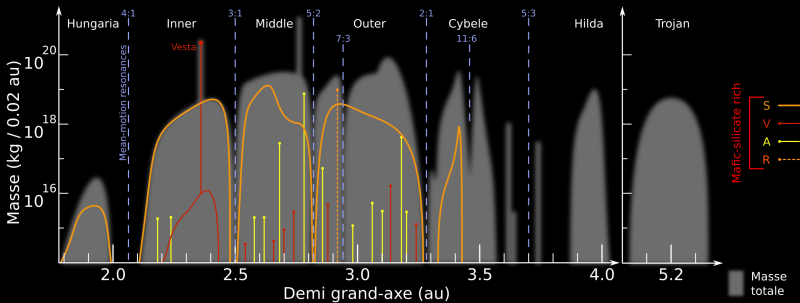
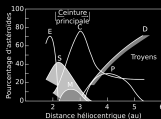
Structure de la ceinture



Structure de la ceinture



Structure de la ceinture



Structure de la ceinture

▶ Au boulot les théoriciens!

- Matériel primitif dans la ceinture interne
- Masse de manteau?
- Répartitions différentes suivant les diamètres

▶ Observateurs: mieux contraindre les densités

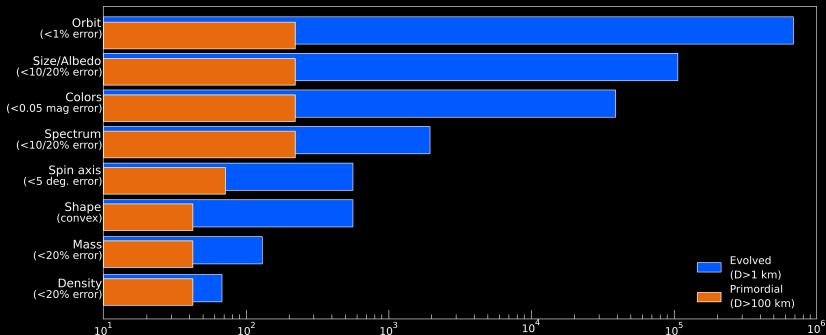
- Densité pour seulement ≈ 300 astéroïdes
- Critique pour convertir **nombre** \rightarrow **masse**
- Courbes de lumière + occultations \rightarrow modèles 3-D

▶ Observateurs: Explorer les propriétés physiques

- Reste *terra incognita*
- Distribution des spins?
- Formes vs composition? vs populations?

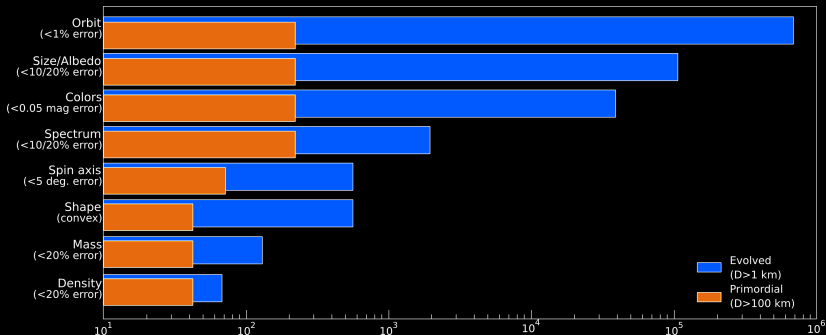
Situation actuelle

● Astéroïdes



Situation actuelle

● Astéroïdes



● TNOs & Comètes

2000 objets → À peine une poignée étudiée

Quelques questions ouvertes

- A. Quelle est la distribution des axes de rotation?
- B. Quelle est la forme des petits corps?
 - Quelle est la distribution des cratères?
 - Pour les comètes, l'activité est-elle liée à la topographie?
- C. Quelle est la structure interne des petits corps?
 - Relation entre densité et composition de surface?
 - Relation entre structure et population?
- D. Quelle est la multiplicité suivant les populations?
 - Est-ce relié à leur formation?
 - Est-ce relié à leur composition?

Quelques questions ouvertes

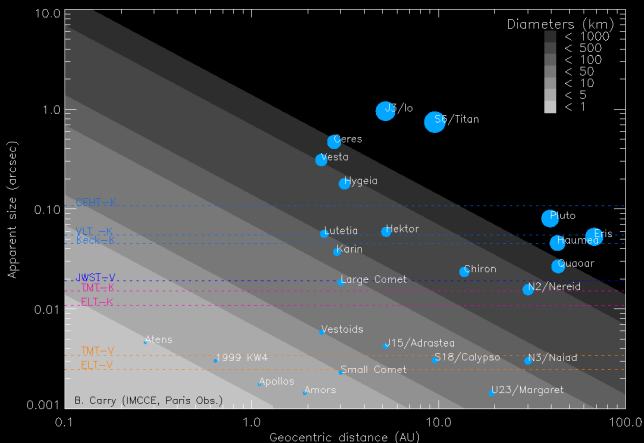
A. Quelle est la distribution des axes de rotation?

B. Quelle est la forme des petits corps?

- Quelle est la distribution des cratères?

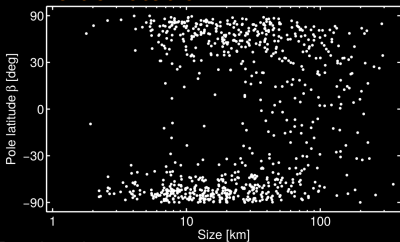
C. Qui

D. Qui



Jetons un oeil...

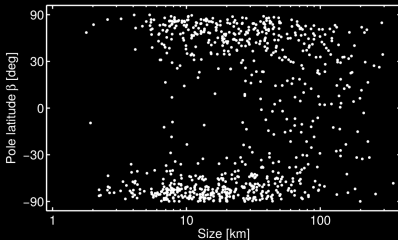
- Axe de rotation



Durech et al. 2015

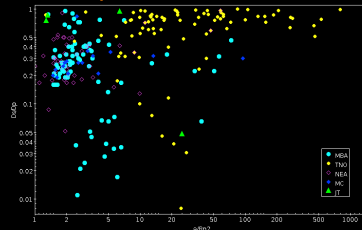
Jetons un oeil...

● Axe de rotation



Durech et al. 2015

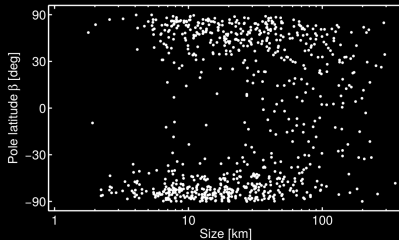
● Multiplicité



Adapté de Johnston 2015

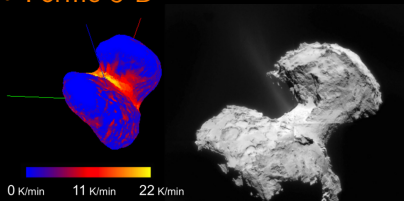
Jetons un oeil...

● Axe de rotation



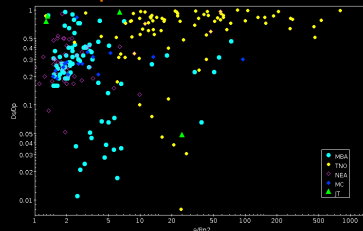
Durech et al. 2015

● Forme 3-D



Ali-Lagoa et al. 2015

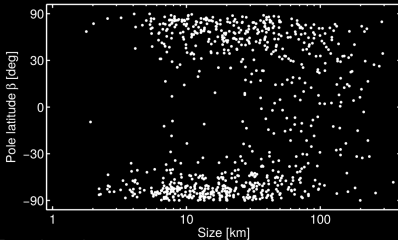
● Multiplicité



Adapté de Johnston 2015

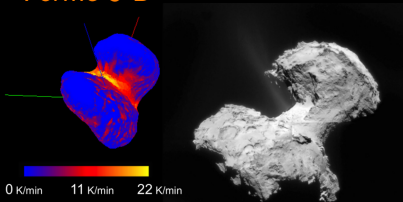
Jetons un oeil...

● Axe de rotation



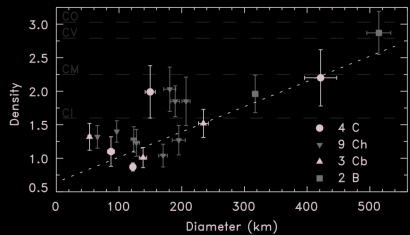
Durech et al. 2015

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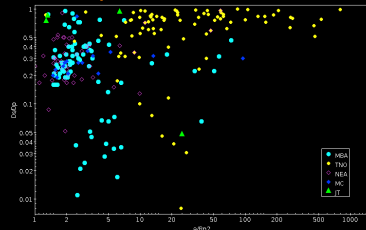
Ali-Lagoa et al. 2015

● Structure interne



Carry 2012

● Multiplicité

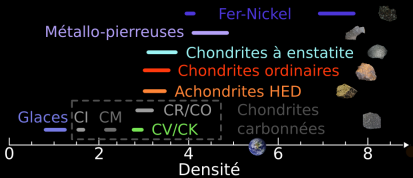


Adapté de Johnston 2015

Densité des petits corps

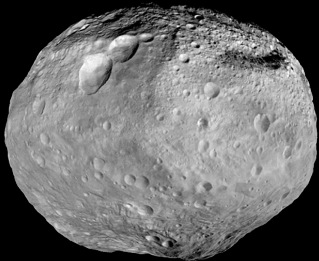
● Densité ⇔ composition

- Glace: $\rho \approx 1 \text{ g.cm}^{-3}$
- Roche: $\rho \approx 2-3 \text{ g.cm}^{-3}$
- Métal: $\rho \approx 7 \text{ g.cm}^{-3}$
- Terre: $\rho = 5.5 \text{ g.cm}^{-3}$



Densité = Masse / Volume

- Satellite → masse
- Forme 3-D → volume



● Imagerie de binaires

- 1990s: Pas d'AO → Pas de satellites
- 2000s: AO → Un satellites
- 2010s: XAO → Deux satellites

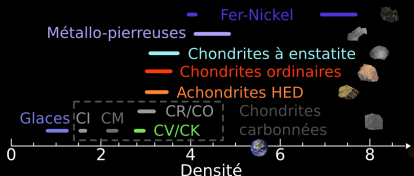
► Forte attente pour E-ELT

► Gaia et occultations stellaires!

Densité des petits corps

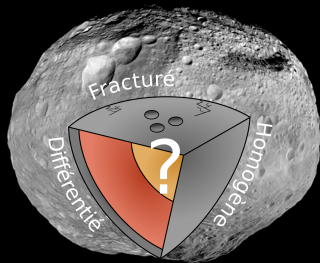
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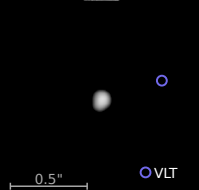
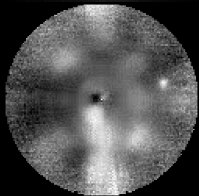
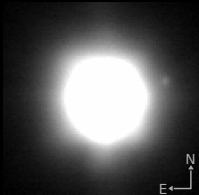
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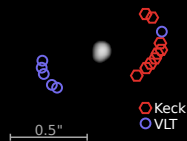
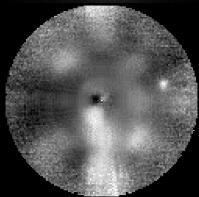
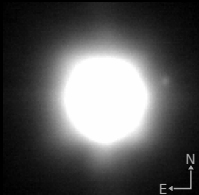
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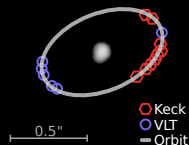
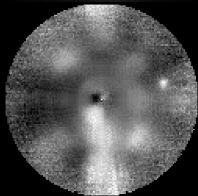
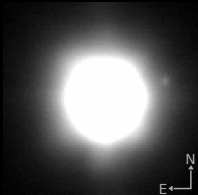


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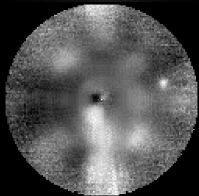
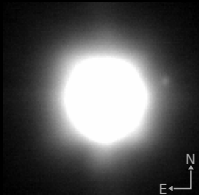


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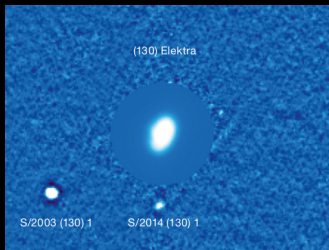
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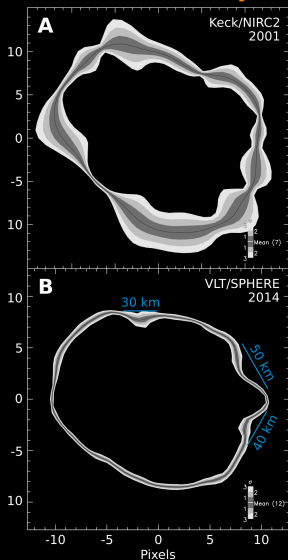
Marchis et al. 2008



Yang et al. 2014

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- ▶ Gaia et occultations stellaires!

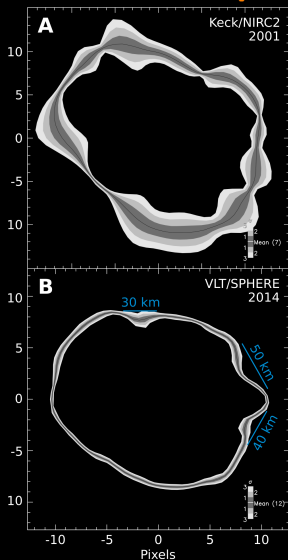
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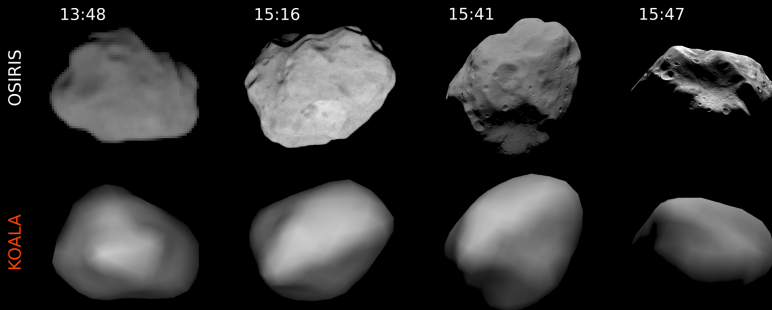
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CdR et forme 3-D



Modèle pre-Flyby
KOALA

Carry et al. 2010

vs. Rosetta
Forme: **2 km**

Carry et al. 2012

Précision
Volume: 15%

Et maintenant?

1. Composition de surface

- Spectroscopie proche IR
- Couleurs SDSS sur certaines niches

2. Propriétés physiques

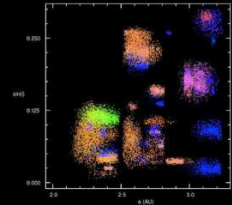
- Courbes de lumière
- Occultations stellaires

3. Multiplicité

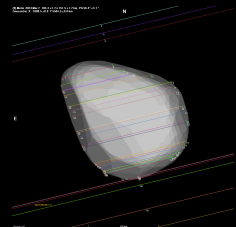
- Courbes de lumière
- Occultations stellaires

► Cibles pour densité

- MPBu 42-3: Hanus



Parker et al. 2008



Euraster.net