Numerical methods in giant planet formation

Dr. Octavio M. Guilera

Instituto de Astrofísica de La Plata (CONICET-UNLP)
Facultad de Ciencias Astronómicas y Geofísicas (UNLP)

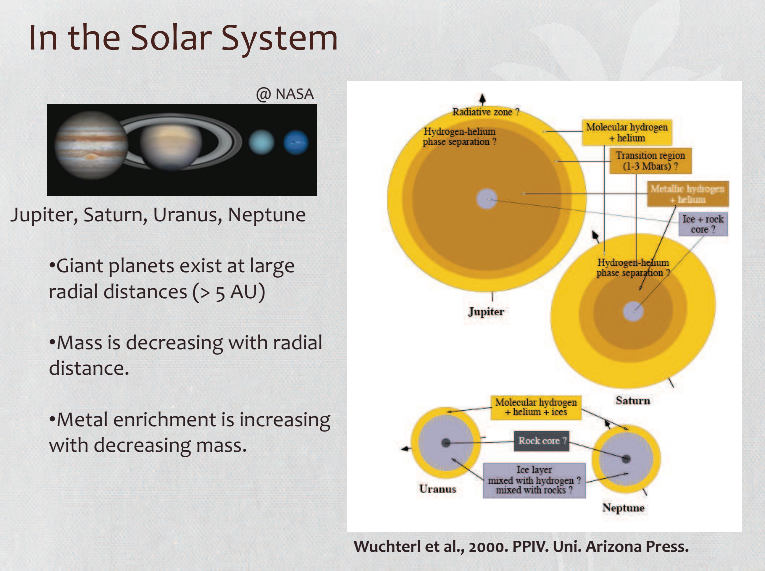
6th. Friends of Friends Meeting
Córdoba, Argentina - February 2016

The importance of giant planets

Why are giant planets importants ?

- They shape the architecture of planetary systems: large masses and fast formation → dominate the dynamics of the system (excitation over small bodies, volatiles delivery, etc.)
- They provide information about physical and chemical properties of the protoplanetary disk where they born.

What do we know about giant planets ?



In the Solar System

@ NASA

Jupiter, Saturn, Uranus, Neptune

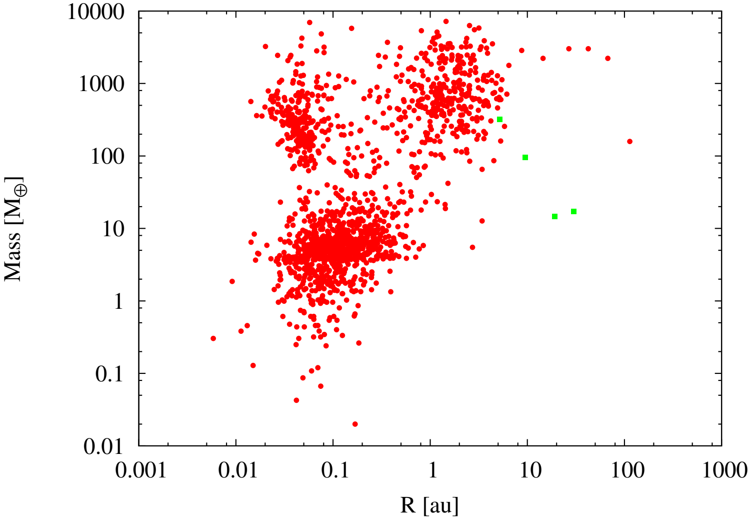
•Giant planets exist at large radial distances (> 5 AU)

•Mass is decreasing with radial distance.

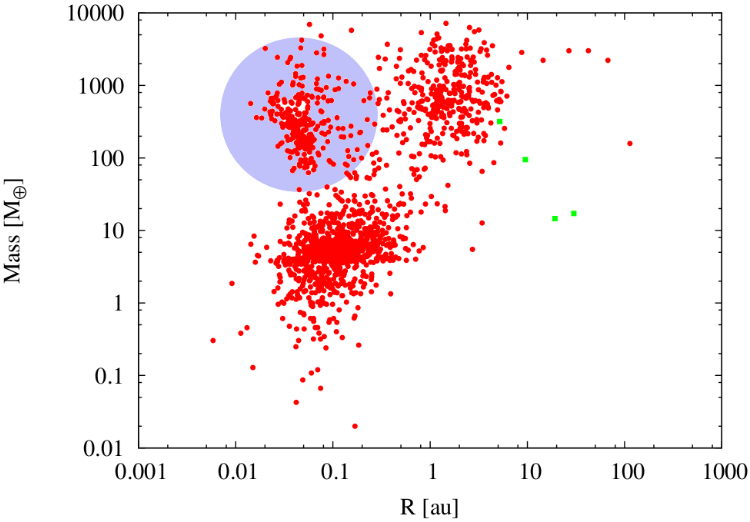
•Metal enrichment is increasing with decreasing mass.

Wuchterl et al., 2000. PPIV. Uni. Arizona Press.

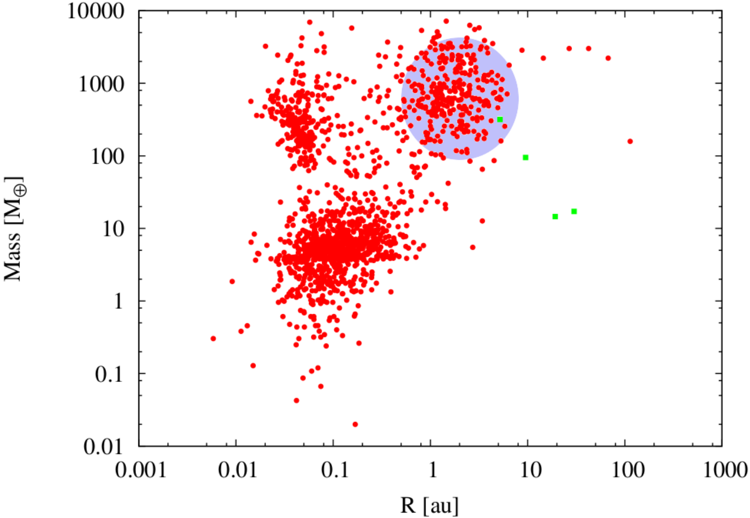
Extrasolar planets



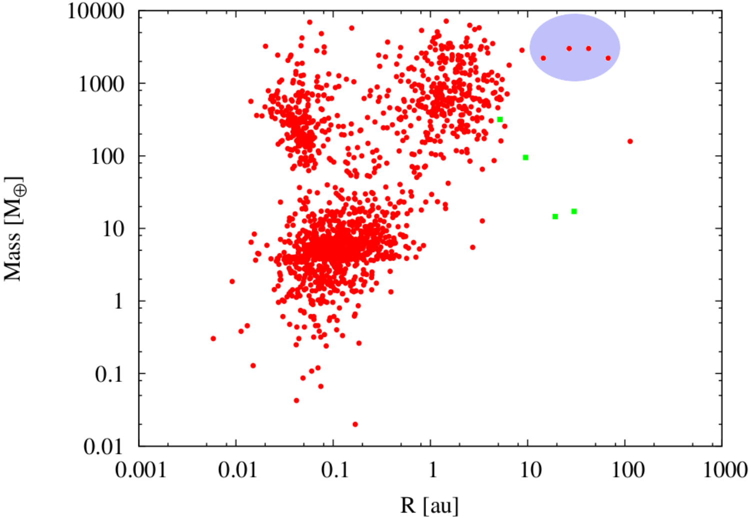
Extrasolar planets



Extrasolar planets

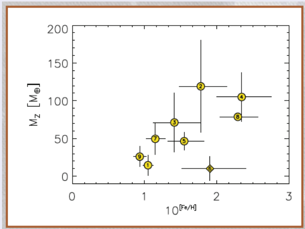


Extrasolar planets

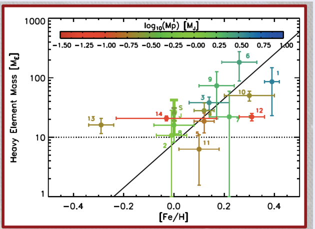


Extrasolar planets

Transiting giant planets are composed by $\sim$ 10-100 $M_\oplus$ of heavy elements.



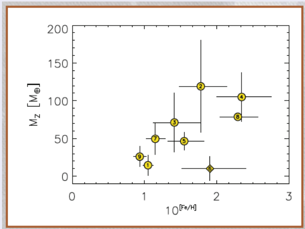
Guillot et al., 2006. A&A, 453, L2.



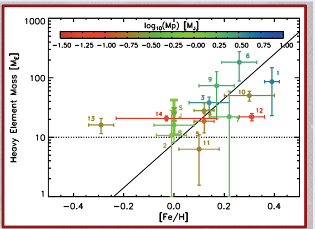
Miller and Fortney, 2011. ApJ, 736, L29.

Extrasolar planets

Transiting giant planets are composed by $\sim$ 10-100 $M_\oplus$ of heavy elements.



Guillot et al., 2006. A&A, 453, L2.

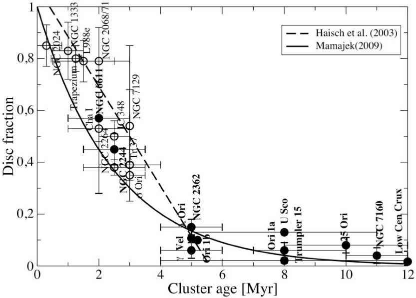


Miller and Fortney, 2011. ApJ, 736, L29.

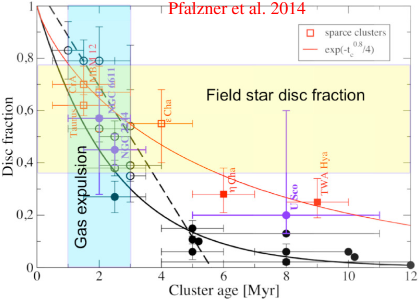
Warning !

- Determination of stellar metallicity is complex.
- Model strongly dependent.

Observational constraints



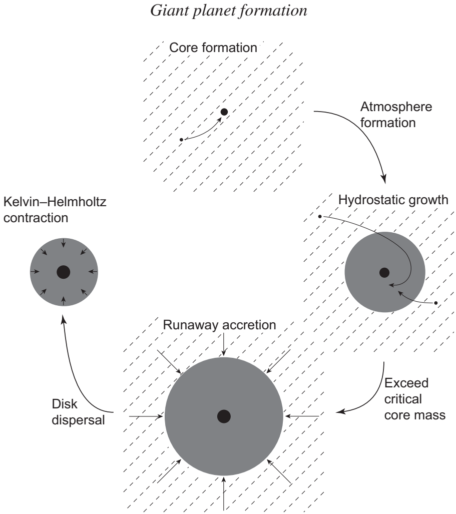
fdisk ~ exp (– t / 2.5 Myr)



Pfalzner et al. 2014

fdisk ~ exp(– t / 4 Myr)

Formation of giant planets: the standard model



- 4 principal stages:
  - **i- formation of a solid core by accretion of planetesimals**
  - **ii- hydrostatic growth of the gaseous envelope**
  - **iii- runaway growth of the gaseous envelope**
  - **iv- ending of the gas accretion, disk dissipation and isolated evolution**

Generalities

In the core accretion model, we can perform numerical simulations where there are three main factors:

- the planetesimal accretion rates to form the core
- the gas accretion rates and the model for the envelope evolution
- the interaction between the envelope and the incoming planetesimals

Generalities

In the core accretion model, we can perform numerical simulations where there are three main factors:

- the planetesimal accretion rates to form the core
- the gas accretion rates and the model for the envelope evolution
- the interaction between the envelope and the incoming planetesimals

Besides ...

- model of disk evolution
- model of planet-disk interaction

Standard equation of stellar evolution ... and more

$$\begin{aligned}
\frac{\partial r}{\partial m_r} &= \frac{1}{4\pi r^2 \rho} && \text{mass definition} \\
\frac{\partial P}{\partial m_r} &= -\frac{G m_r}{4\pi r^4} && \text{hydrostratic equilibrium} \\
\frac{\partial L_r}{\partial m_r} &= \epsilon_{pl} - T\frac{\partial S}{\partial t} && \text{energy conservation} \\
\frac{\partial T}{\partial m_r} &= -\frac{G m_r T}{4\pi r^4 P}\nabla && \text{energy transport}
\end{aligned}$$

Standard equation of stellar evolution ... and more

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$$

mass definition

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$

hydrostratic equilibrium

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{pl} - T\frac{\partial S}{\partial t}$$

energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$

energy transport

- $P = P(\rho, T)$ SCHV94 (EOS for giant planets and brown dwarf)
- $dM_C/dt = \Sigma_p(R_P)\Omega_k(R_P)\mathrm{R}_{\mathrm{H}}^2 P_{\mathrm{coll}} \rightarrow \epsilon_{pl}$
- evolution of gas disk → α accretion disk + photoevaporation
- evolution of the planetesimal population → migration + accretion + collisional evolution
- planet-disk interaction → type I and type II migration

Standard equation of stellar evolution ... and more

$$
\begin{aligned}
\frac{\partial r}{\partial m_r} &= \frac{1}{4\pi r^2 \rho} && \text{mass definition}\\
\frac{\partial P}{\partial m_r} &= -\frac{G m_r}{4\pi r^4} && \text{hydrostratic equilibrium}\\
\frac{\partial L_r}{\partial m_r} &= \epsilon_{pl} - T\frac{\partial S}{\partial t} && \text{energy conservation}\\
\frac{\partial T}{\partial m_r} &= -\frac{G m_r T}{4\pi r^4 P}\nabla && \text{energy transport}
\end{aligned}
$$

- $P = P(\rho, T)$ SCHV94 (EOS for giant planets and brown dwarf)
- $d\mathrm{M_C}/dt = \Sigma_p(R_P)\Omega_k(R_P)\mathrm{R}_{\mathrm{H}}^2 P_{\mathrm{coll}} \rightarrow \epsilon_{pl}$
- evolution of gas disk → α accretion disk + photoevaporation
- evolution of the planetesimal population → migration + accretion + collisional evolution
- planet-disk interaction → type I and type II migration

Standard equation of stellar evolution ... and more

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$$ mass definition

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$ hydrostratic equilibrium

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{pl} - T\frac{\partial S}{\partial t}$$ energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$ energy transport

- $P = P(\rho, T)$ SCHV94 (EOS for giant planets and brown dwarf)
- $d\mathrm{M_C}/dt = \Sigma_p(R_P)\Omega_k(R_P)\mathrm{R}_\mathrm{H}^2 P_{\mathrm{coll}} \rightarrow \epsilon_{pl}$
- evolution of gas disk → α accretion disk + photoevaporation
- evolution of the planetesimal population → migration + accretion + collisional evolution
- planet-disk interaction → type I and type II migration

Standard equation of stellar evolution ... and more

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$$ mass definition

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$ hydrostratic equilibrium

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{pl} - T\frac{\partial S}{\partial t}$$ energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$ energy transport

- $P = P(\rho, T)$ SCHV94 (EOS for giant planets and brown dwarf)
- $d\mathrm{M_C}/dt = \Sigma_p(R_P)\Omega_k(R_P)\mathrm{R_H^2}P_{\mathrm{coll}} \to \epsilon_{pl}$
- evolution of gas disk → α accretion disk + photoevaporation
- evolution of the planetesimal population → migration + accretion + collisional evolution
- planet-disk interaction → type I and type II migration

Standard equation of stellar evolution ... and more

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$$ mass definition

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$ hydrostratic equilibrium

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{pl} - T\frac{\partial S}{\partial t}$$ energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$ energy transport

- $P = P(\rho, T)$ SCHV94 (EOS for giant planets and brown dwarf)
- $d\mathrm{M_C}/dt = \Sigma_p(R_P)\Omega_k(R_P)\mathrm{R}_{\mathrm{H}}^2 P_{\mathrm{coll}} \rightarrow \epsilon_{pl}$
- evolution of gas disk → α accretion disk + photoevaporation
- evolution of the planetesimal population → migration + accretion + collisional evolution
- planet-disk interaction → type I and type II migration

First full calculations of giant planet formation

Pollack et al. (1996)

- four structure equations (envelope) + planetesimal accretion rate (core)

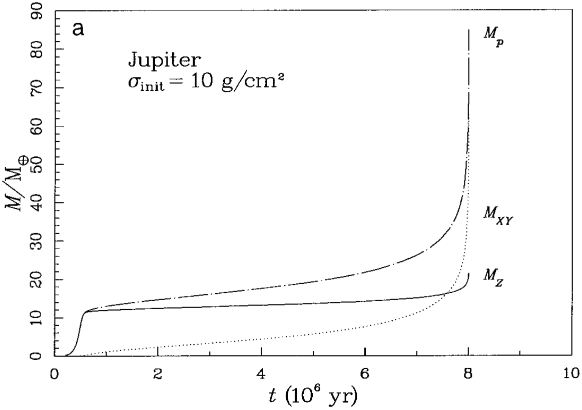


Figure : Baseline model for Jupiter formation

First full calculations of giant planet formation

Pollack et al. (1996)

- four structure equations (envelope) + planetesimal accretion rate (core)

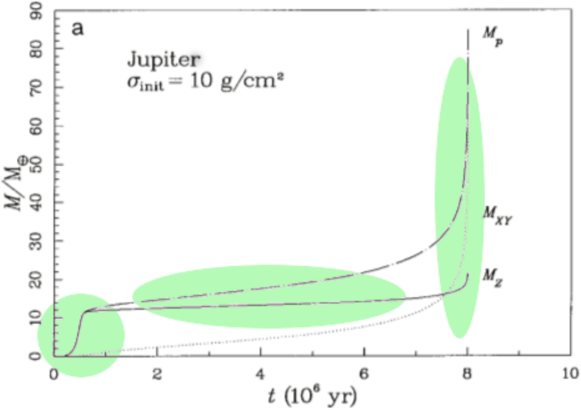


Figure : Baseline model for Jupiter formation

First full calculations of giant planet formation

Pollack et al. (1996)

- four structure equations (envelope) + planetesimal accretion rate (core)

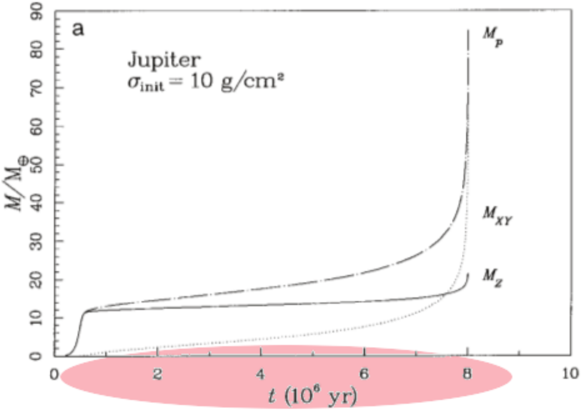
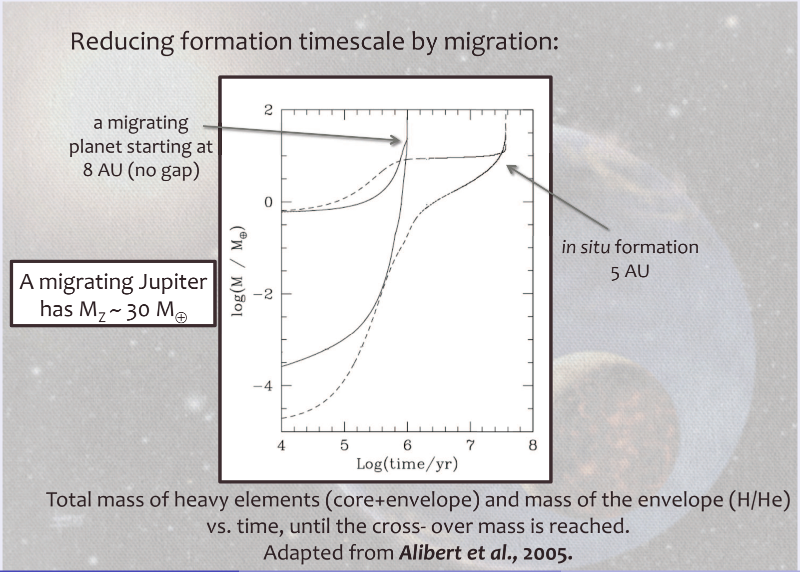


Figure : Baseline model for Jupiter formation

Giant planet formation + disk evolution

Alibert et al. (2005): models of planet formation + disk evolution



Reducing formation timescale by migration:

a migrating planet starting at 8 AU (no gap)

in situ formation 5 AU

A migrating Jupiter has $M_Z \sim 30\ M_\oplus$

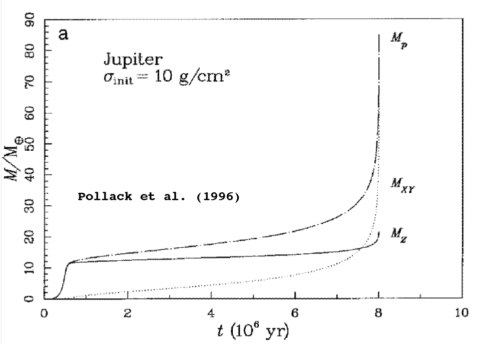
Total mass of heavy elements (core+envelope) and mass of the envelope (H/He) vs. time, until the cross- over mass is reached.
Adapted from ***Alibert et al.*, 2005.**

Common assumptions of these models

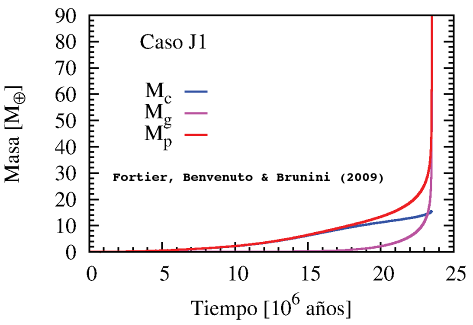
- Big planetesimals →∼ 100 km
- Isolated formation
- The planetesimal population only evolves by planet accretion
- **Unrealistic planetesimal accretion rates** → shear keplerian regime → the planet does not exite the planetesimals

Oligarchic grow regime and giant planet formation

Oligarchic grow → the planet exites the surrounding planetesimals



Pollack et al. (1996)



Fortier, Benvenuto & Brunini (2009)

Oligarchic grow regime and giant planet formation

Reducing formation timescale reducing planetesimal size

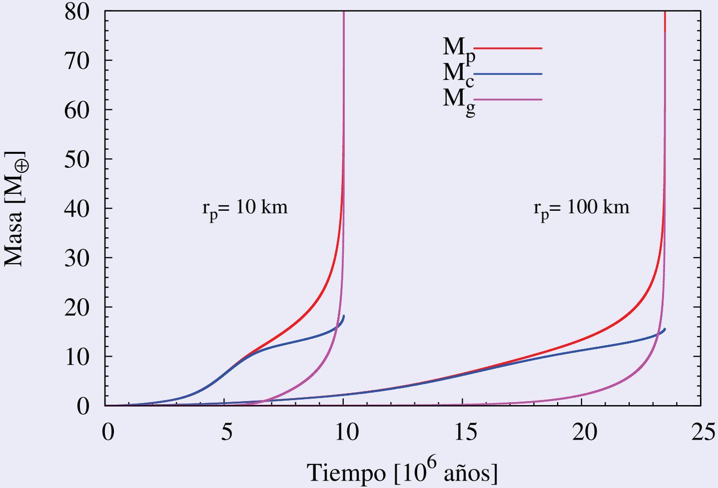
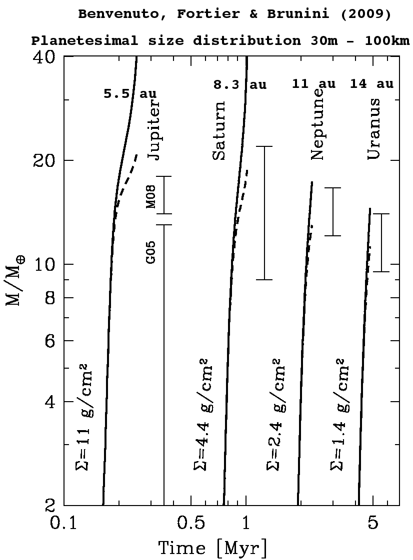


Figure : Fortier PhD Thesis

Planetesimal size distribution

Isolated formation of Solar System giant planets

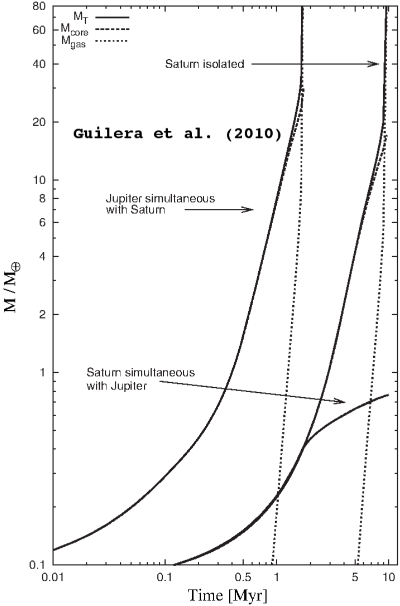


Simultaneous formation of giant planets

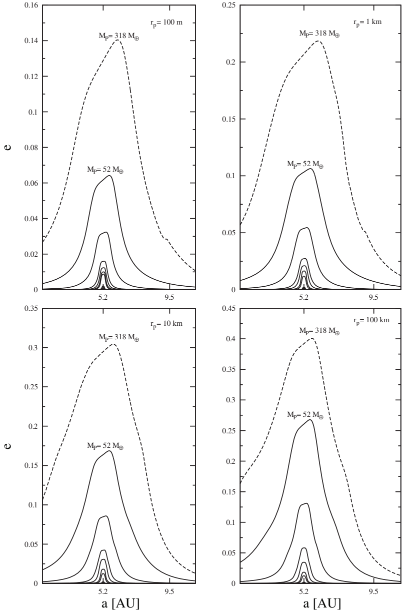
Guilera et al. (2010)

- Planets inmmersed in a disk of gas and planetesimales
- Planetesimal size distribution between 100 m and 100 km
- Planetesimal migration is considered
- Planets exite planetesimal eccentricities and inclinations → increase planetesimal migration
- No gravitational interaction: two planets growing simultaneously in a disk perturbing the population of planetesimals

Simultaneous formation of giant planets



Simultaneous formation of giant planets



Planet population synthesis

Fortier et al. (2013)

- Incorporation of the oligarchic growth in the Bernese Model
- Detailed study of the rate of giant planet formation as function of the planetesimal size
- Detailed model of planet formation + disk evolution + planet migration
- 10000 simulations per planetimal size

Planet population synthesis

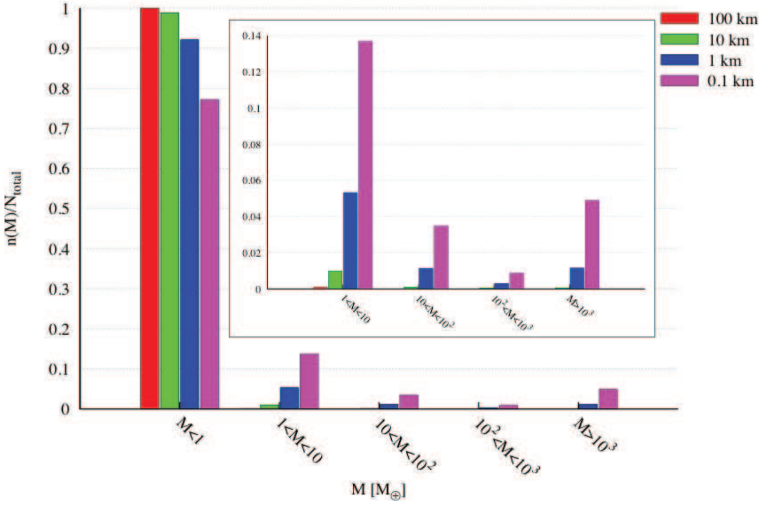


Figure : Fortier et al. (2013)

Planet population synthesis

Alibert et al. (2013): N body interacction

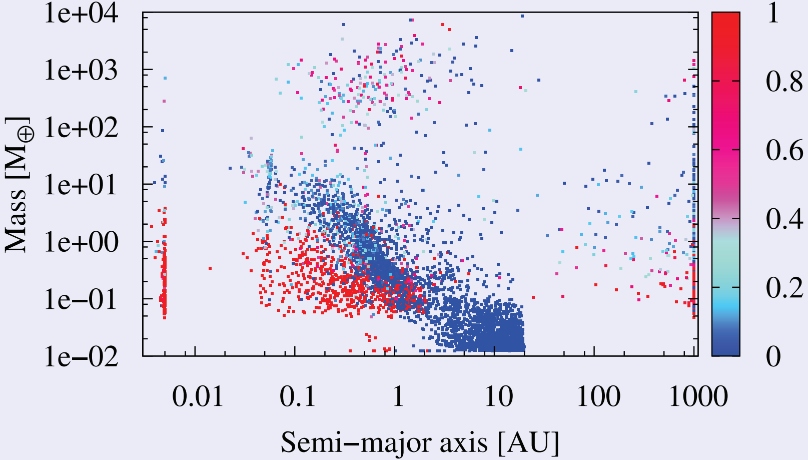


Figure : Mass vs. semi-major axis diagram from planetesimals of 100 m

Planetesimal collisional evolution

- All these models do not include planetesimal collisional evolution
- Low planetesimal relative velocities → coagulation between planetesimals
- High planetesimal relative velocities → fragmentation between planetesimals
- As planet grow it increases planetesimal relative velocities

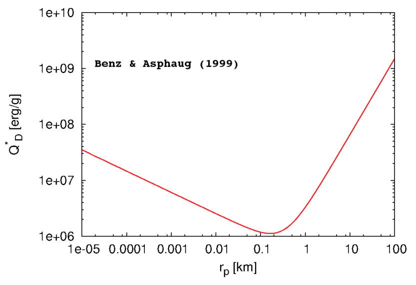
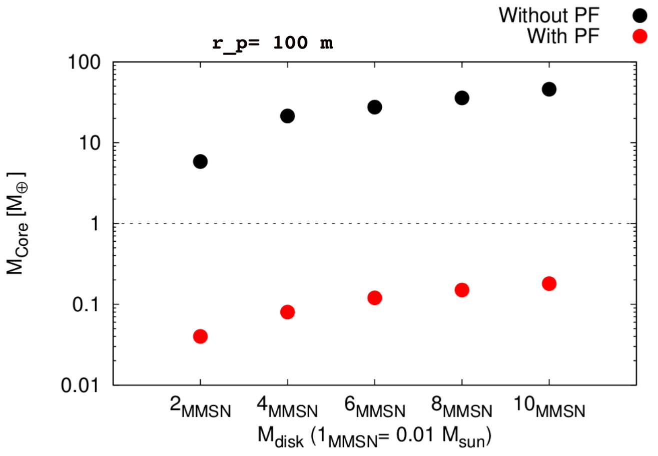


Figure : Planetesimal of ∼ 100 m of radii are the easiest to fragment

Planetesimal collisional evolution

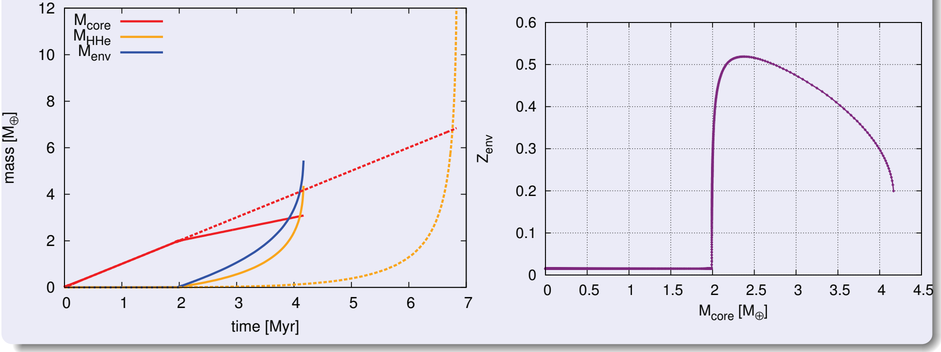
Guilera et al. (2014)



Pollution of the envelope

- All previous works assume envelopes of solar composition and that planetesimals deposite all the mass in the core
- But, accretion of planetesimals enrich the envelope with heavy elements
- Changes in the EOS and opacities → very complex problem

Courtesy of Julia Venturini (Venturini et al. (2016) in prep.)



Sumary

- Models fit well the physical properties of the Solar System giant planets
- Models predict a large variety of masses and compositions (gas giant planets and ice giant planets)
- A significant amount of solid mass in small planetesimals is needed to form giant planets if oligarchic growth is considered
- Isolated formation can drastically change by the presence of other planets (N body interacctions and perturbations in the population of planetesimals)
- The collisional evolution of the population of planetesimals can inhibits the formation of massive cores (more accurate models are needed)
- The enrichment of the envelope could significantly reduce formation time-scales

Open questions

- Initial sizes of planetesimals
- Type I migration
- Final masses of giant planets
- Initial structures and dissipation of the disks