Thermal torque effects on the migration of growing low-mass planets

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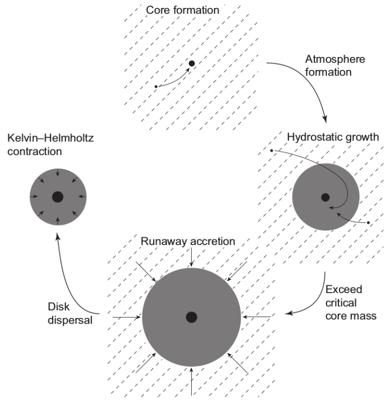
Great Barriers in Planet Formation

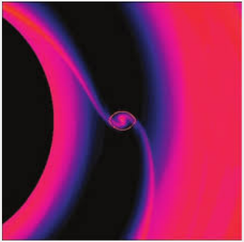
Formation of terrestrial and giant planets



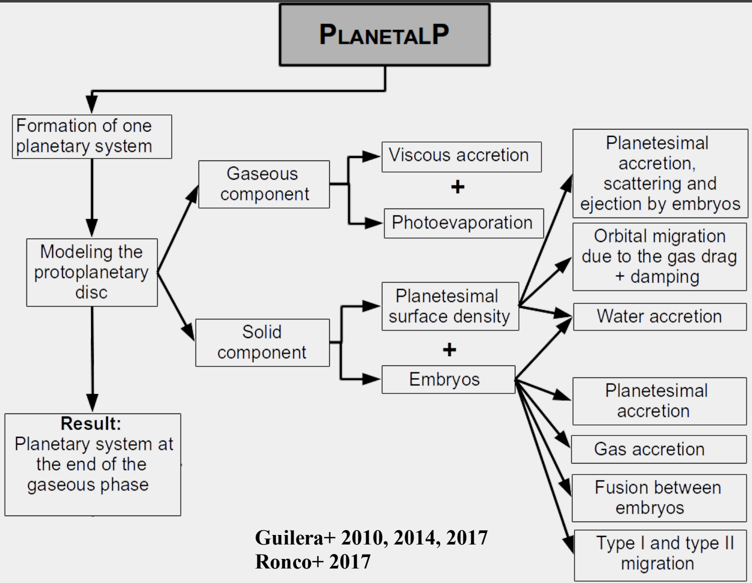
Armitage 2010

- 4 principal stages:
  - **i-** a solid core of about the mass of the Moon grows by the accretion of planetesimals or pebbles
  - **ii-** as the solid core grows the planet accretes the surrounding gas, and the envelope grows in hydrostatic equilibrium
  - **iii-** when the mass of the envelope equals the mass of the core, the gaseous runaway growth starts
  - **iv-** the gas accretion stops (very massive giant planet or disk dissipation)

- gravitational interactions between a planet and the gas disk produce a torque that modifies the orbit of the planet.
- two limit cases: type I migration (low-mass and intermediate-mass planets that can not open a gap in the gas disk), and type II migration (massive planets able to open a gap in the gas disk, in general gaseous giant planets).

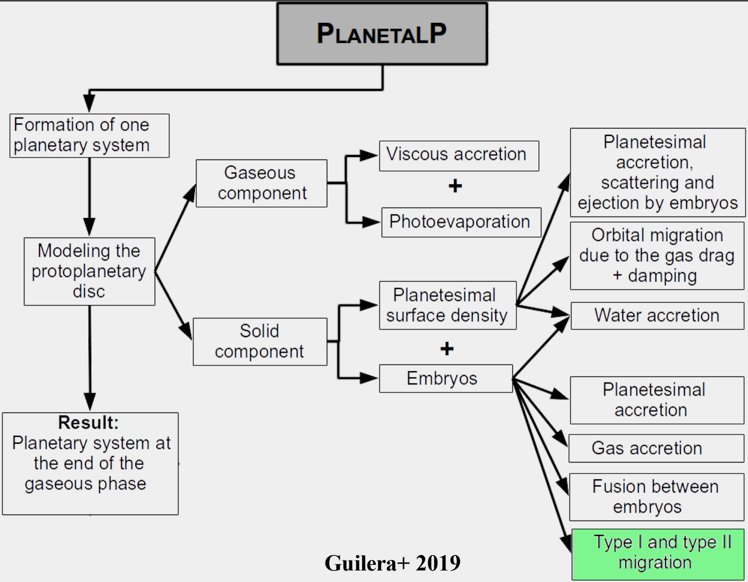


Our planet formation model



Guilera+ 2010, 2014, 2017
Ronco+ 2017

Our planet formation model



Guilera+ 2019

Previous torques

Most used type I migration prescriptions derived from 2D non-isothermal hydrodynamical simulations by Paardekooper et al. (2011):

$$\Gamma = \Gamma_{\mathrm{L}} + \Gamma_{\mathrm{C}}$$

$$\Gamma_{\mathrm{C}} = \Gamma_{\mathrm{C,bar}} + \Gamma_{\mathrm{C,ent}}$$

Previous torques

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$$\Gamma_{\mathrm{C}} = \Gamma_{\mathrm{C,bar}} + \Gamma_{\mathrm{C,ent}}$$

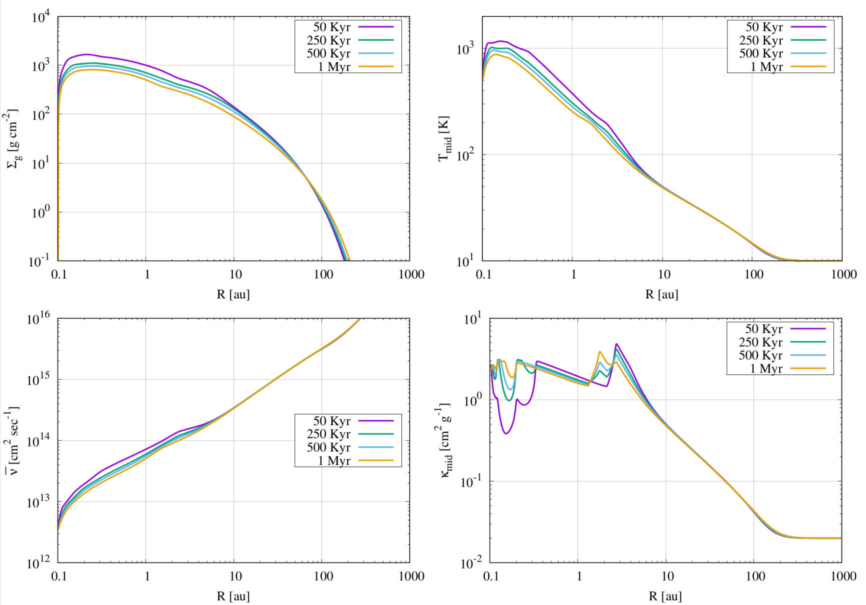
Updated torques

Improved type I migration prescriptions derived from 3D non-isothermal hydrodynamical simulations by Jimenez & Masset (2017):

$$\Gamma = \Gamma_{\mathrm{L}} + \Gamma_{\mathrm{C}}$$

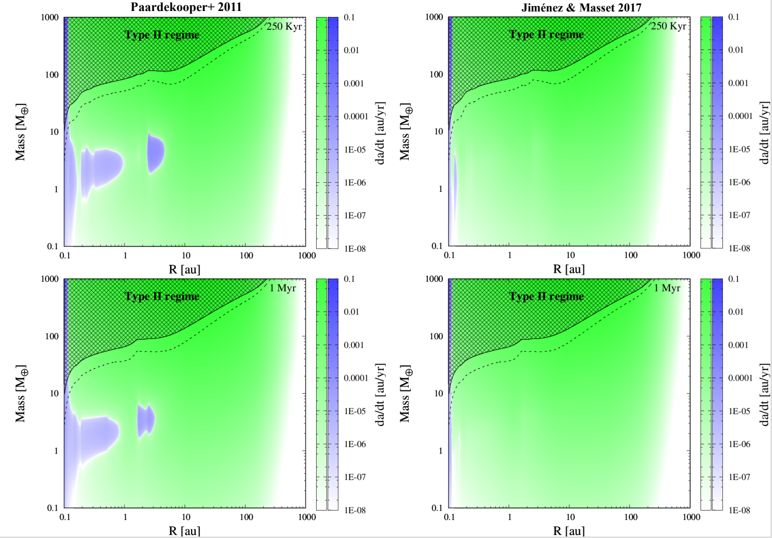
$$\Gamma_{\mathrm{C}} = \Gamma_{\mathrm{C,vor}} + \Gamma_{\mathrm{C,ent}} + \Gamma_{\mathrm{C,temp}} + \Gamma_{\mathrm{C,vv}}$$

Results

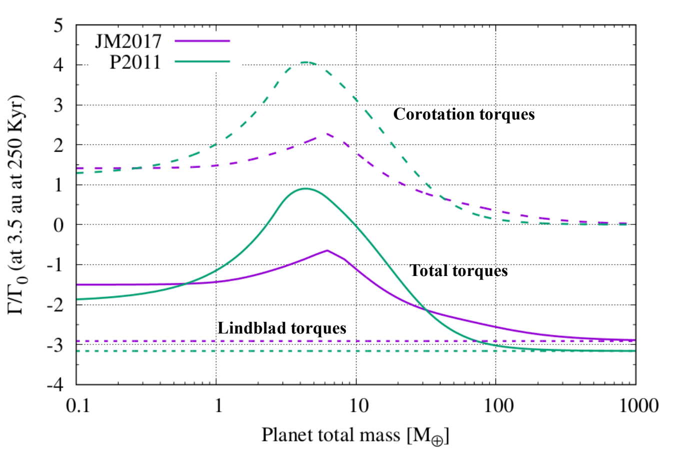


Σ_g [g cm^{-2}]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0.1
1
10
100
1000
R [au]
50 Kyr
250 Kyr
500 Kyr
1 Myr
T_{mid} [K]
10^{3}
10^{2}
10^{1}
0.1
1
10
100
1000
R [au]
50 Kyr
250 Kyr
500 Kyr
1 Myr
$\bar{\nu}$ [cm^{2} sec^{-1}]
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0.1
1
10
100
1000
R [au]
50 Kyr
250 Kyr
500 Kyr
1 Myr
κ_{mid} [cm^{2} g^{-1}]
10^{1}
10^{0}
10^{-1}
10^{-2}
0.1
1
10
100
1000
R [au]
50 Kyr
250 Kyr
500 Kyr
1 Myr

Migration maps from 2D anb 3D hydrodynamical simulations



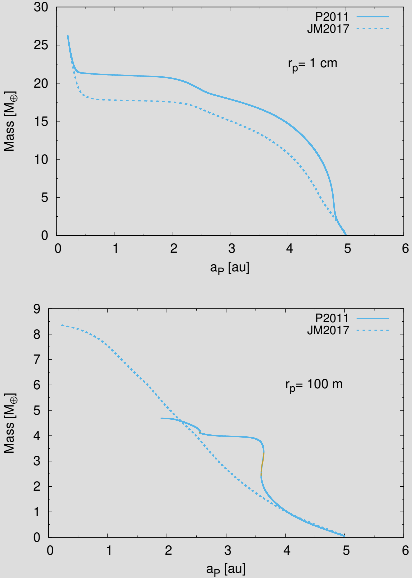
Migration maps from 2D anb 3D hydrodynamical simulations



0.1 1 10 100 1000
R [au]

0.1 1 10 100 1000
R [au]

Planet formation from both models



Incorporation of the thermal torque

- Lega et al (2014) found that very close to a low-mass planet the gas is more cold and dense than it would be if it behaved adiabatically $\rightarrow$ netative torque (inward migration)
- Benitez-Llambay et al. (2015) found that the heat released by a planet due to solid accretion is diffused in the nearby disc generating two asymmetric hot and low-density lobes $\rightarrow$ positive torque (outward migration)
- Recentenly, Masset (2017) developed analytical prescription for both torques:

$$\Gamma_{\text{thermal}} = \Gamma_{\text{cold}} + \Gamma_{\text{heating}}$$

Incorporation of the thermal torque

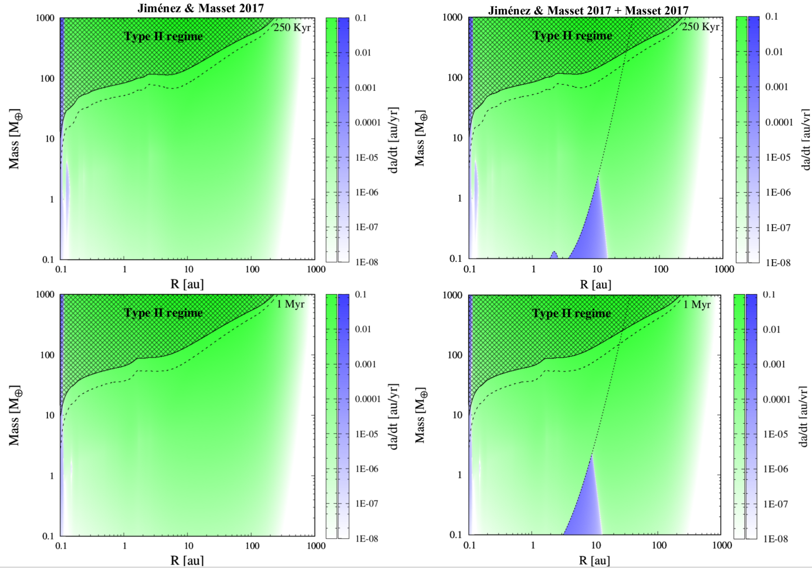
- Lega et al (2014) found that very close to a low-mass planet the gas is more cold and dense than it would be if it behaved adiabatically $\rightarrow$ netative torque (inward migration)

New total torque

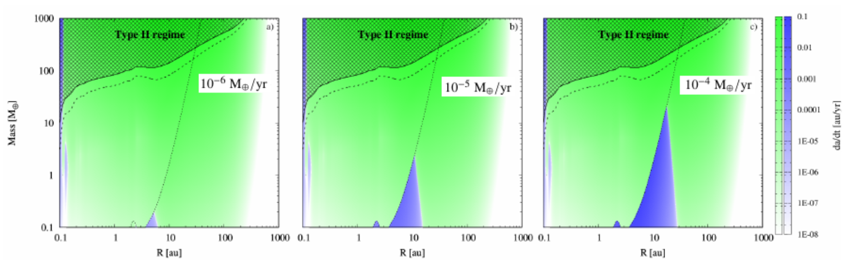
$$\Gamma_{\text{total}} = \Gamma_{\text{type I}} + \Gamma_{\text{thermal}}$$

$$\begin{aligned}\Gamma_{\text{total}} = \quad & \Gamma_{\text{L}} + \Gamma_{\text{C}} \quad \text{(Jimenez \& Masset 2017)} + \\ & \Gamma_{\text{cold}} + \Gamma_{\text{heating}} \quad \text{(Masset 2017)}\end{aligned}$$

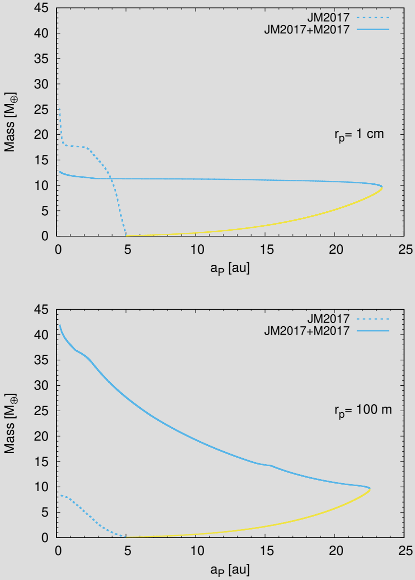
Migration maps including the thermal torque



Thermal torque dependence with the solid accretion rate



Planet formation from both models



- We incorporated in our model the updated type I migration rates from 3D hydrodynamical simulations (Jimenez & Masset 2017).
- Planet formation tracks could be very differents respect to the most used type I migrations rates from 2D hydrodynamical simulations (Paardekooper+ 2011).
- We incorporated for the first time the thermal torque to study how it impacts in the formation of a planet from early stages.
- **We showed that the heating torque, can change drastically the planet formation track. If the solid accretion rate is high, the planet can significantly migrate outward. This phenomenon could help in the formation and survival of giant planets at moderate distances from the central star.**