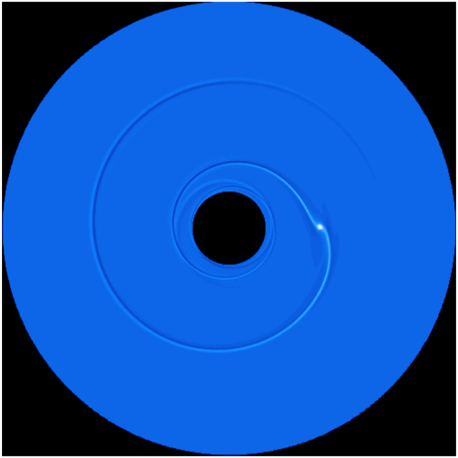
Heating torque on low mass planets

P. Benítez-Llambay[1], F. Masset[2⋆], G. Koenigsberger[2], J. Szulágyi[3]

1. Córdoba Univ, Argentina, 2. UNAM, Mexico, 3. OCA, France

Disk torque on low mass planet

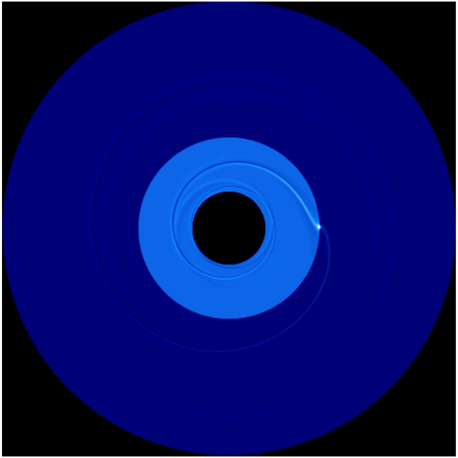
Planet in circular orbit embedded in a Keplerian disk



The planet excites a one-armed spiral wake

Disk torque on low mass planet

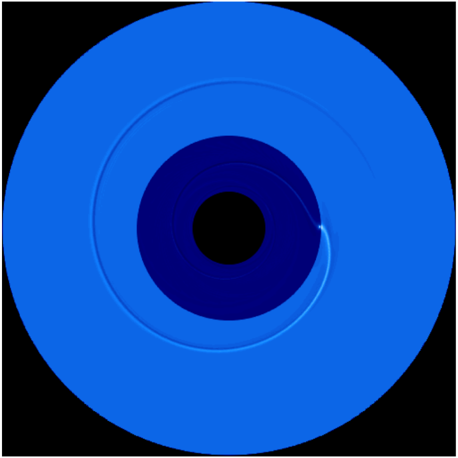
Planet in circular orbit embedded in a Keplerian disk



In the inner disk, the wake is leading the planet $\Longrightarrow$ **positive** torque arises from inner disk

Disk torque on low mass planet

Planet in circular orbit embedded in a Keplerian disk



In the outer disk, the wake is behind the planet $\Longrightarrow$ **negative** torque arises from outer disk

Net wake torque: differential Lindblad torque

- For small mass planets, wake = linear superposition of waves launched at the Outer and Inner Lindblad resonances
- Outer and inner torque have large absolute values. The net torque, their sum, is a not so small fraction of them
- Generally negative, this torque can lead to a fast decay of a planet toward its star. The more massive the planet, the faster this decay

Net wake torque: differential Lindblad torque

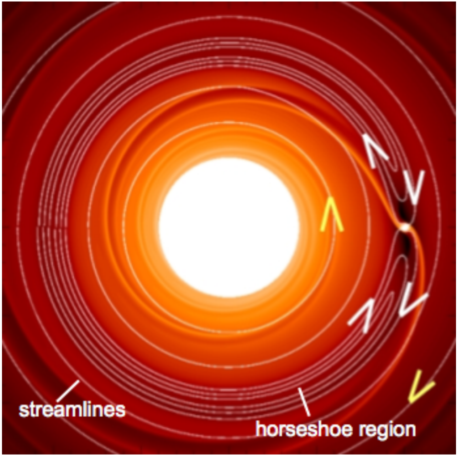
- For small mass planets, wake = linear superposition of waves launched at the Outer and Inner Lindblad resonances
- Outer and inner torque have large absolute values. The net torque, their sum, is a not so small fraction of them
- Generally negative, this torque can lead to a fast decay of a planet toward its star. The more massive the planet, the faster this decay

Net wake torque: differential Lindblad torque

- For small mass planets, wake = linear superposition of waves launched at the Outer and Inner Lindblad resonances
- Outer and inner torque have large absolute values. The net torque, their sum, is a not so small fraction of them
- Generally negative, this torque can lead to a fast decay of a planet toward its star. The more massive the planet, the faster this decay

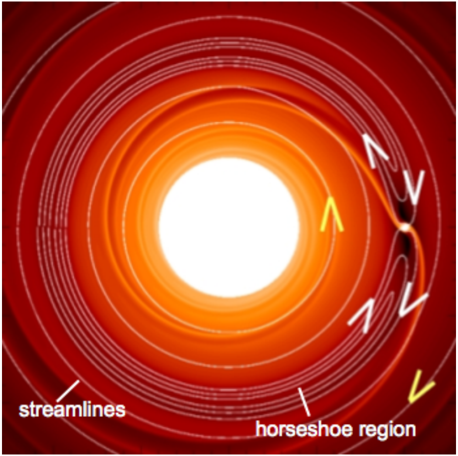
A few 10^5 *years for* $1\ M_\oplus$ *in the MMSN at 1 AU.*

Corotation torque



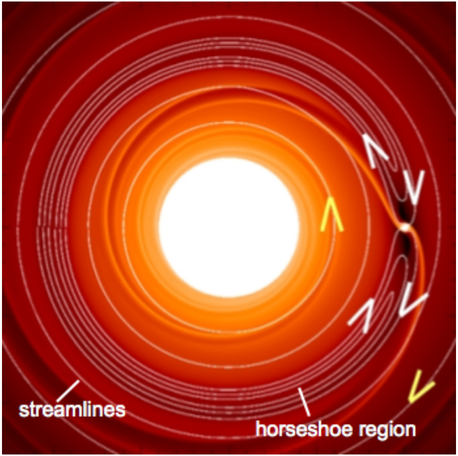
Horseshoe region: streamlines that *librate* near the orbit and exchange angular momentum with the planet as they perform U-turns

Corotation torque



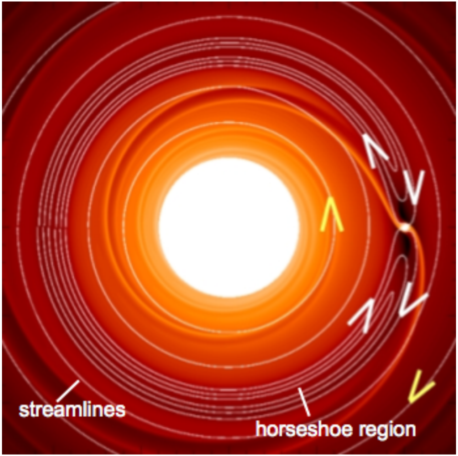
This corresponds to the corotation torque

Corotation torque



Total torque is the sum of corotation and differential Lindblad torques

Corotation torque



The corotation torque depends on gradients across the orbit, in particular the gradient of entropy

Impact of heat released by planet?

- Torque sensitive to entropy distribution near the planet
- Planetary mass growth releases entropy in the surrounding nebula
- $\Longrightarrow$ incorporate heat release to planet in disk model

Impact of heat released by planet?

- Torque sensitive to entropy distribution near the planet
- Planetary mass growth releases entropy in the surrounding nebula
- $\Longrightarrow$ incorporate heat release to planet in disk model

Impact of heat released by planet?

- Torque sensitive to entropy distribution near the planet
- Planetary mass growth releases entropy in the surrounding nebula
- $\Longrightarrow$ incorporate heat release to planet in disk model

Heat release by planet

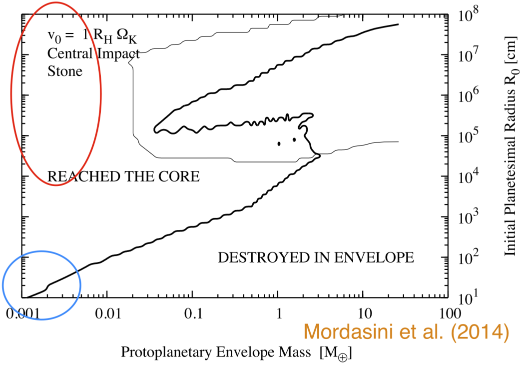
Small mass planet ($\lesssim 5\ M_\oplus$) bombarded by solid material which releases heat at the rate:

$$\dot{E} = \frac{GM_p\dot{M}_p}{R_p}$$

Assumes all infalling bodies reach the planet's surface.

- Largely satisfied for planetesimal accretion
- Barely so for pebble accretion

Heat release by planet



Mordasini et al. (2014)

- Largely satisfied for planetesimal accretion
- Barely so for pebble accretion

Numerical procedure

- Solve hydrodynamics equation on spherical mesh
- Solve radiative transfer equations (grey approximation + FLD)
- Start with a disk in thermal and hydrostatic equilibrium (heating source: viscous heating).
- Release heat in the cells surrounding the planet

Numerical procedure

- Solve hydrodynamics equation on spherical mesh
- Solve radiative transfer equations (grey approximation + FLD)
- Start with a disk in thermal and hydrostatic equilibrium (heating source: viscous heating).
- Release heat in the cells surrounding the planet

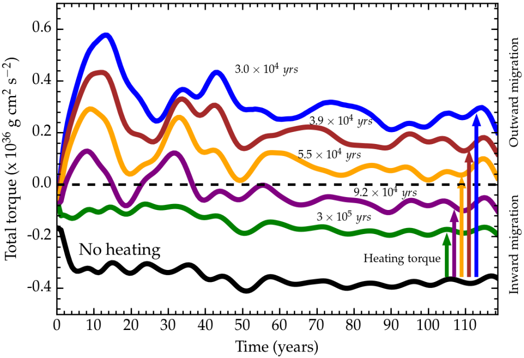
Numerical procedure

- Solve hydrodynamics equation on spherical mesh
- Solve radiative transfer equations (grey approximation + FLD)
- Start with a disk in thermal and hydrostatic equilibrium (heating source: viscous heating).
- Release heat in the cells surrounding the planet

Numerical procedure

- Solve hydrodynamics equation on spherical mesh
- Solve radiative transfer equations (grey approximation + FLD)
- Start with a disk in thermal and hydrostatic equilibrium (heating source: viscous heating).
- Release heat in the cells surrounding the planet

Results of fiducial calculation



3 $M_\oplus$ planet at 5.2 AU

Disk viscosity 10^{15} cm^2

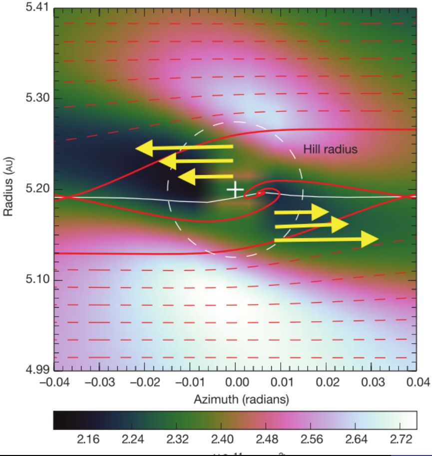
Opacity $\kappa = 1$ cm^2.g^{-1}

Planet density $\rho = 3$ g.cm^{-3}

Torque reversal for mass doubling time $\lesssim 10^5$ yrs

Why is the heating torque positive - 1?

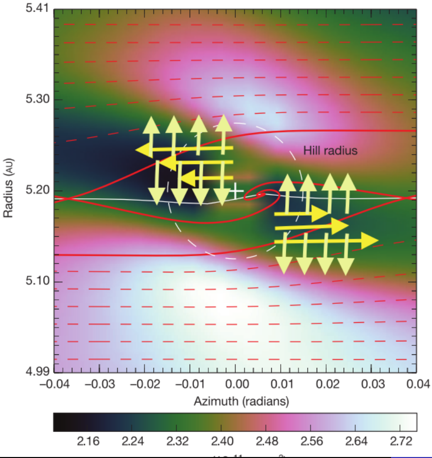
The heat released is subject to an advection-diffusion problem.
Heated gas is under-dense.



Advection by the Keplerian flow

Why is the heating torque positive - 1?

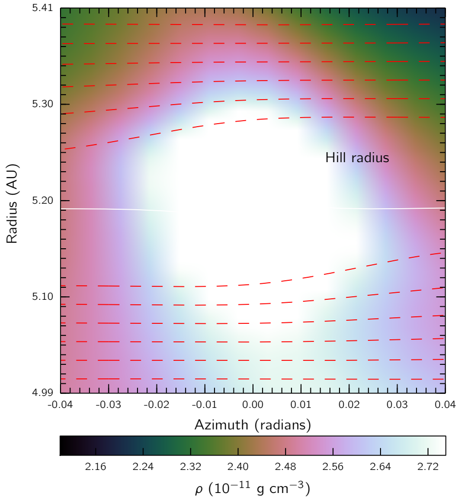
The heat released is subject to an advection-diffusion problem. Heated gas is under-dense.



Diffusion by radiative transfer

Why is the heating torque positive - 2?

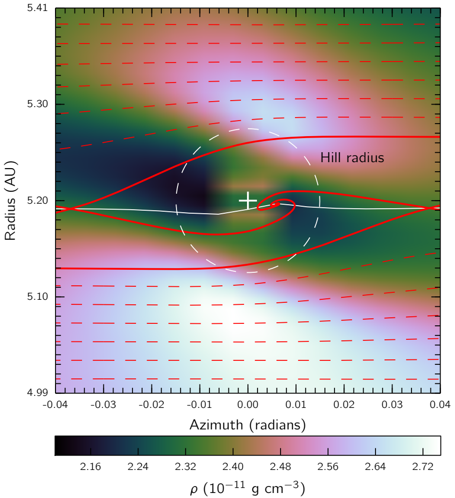
Density in the disk midplane



No heat release: large density values in the planet vicinity

Why is the heating torque positive - 2?

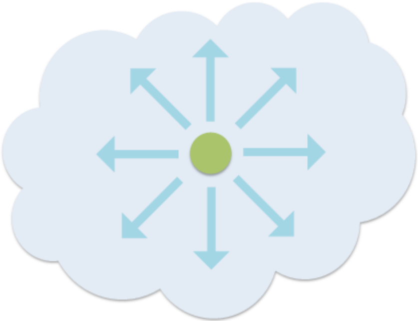
Density in the disk midplane



Heat release: two under-dense lobes on each side of planet

Why is the heating torque positive - 2?

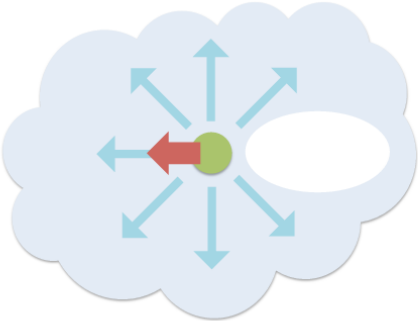
Density in the disk midplane



Idealized situation
Uniform density $\Rightarrow$ no net force

Why is the heating torque positive - 2?

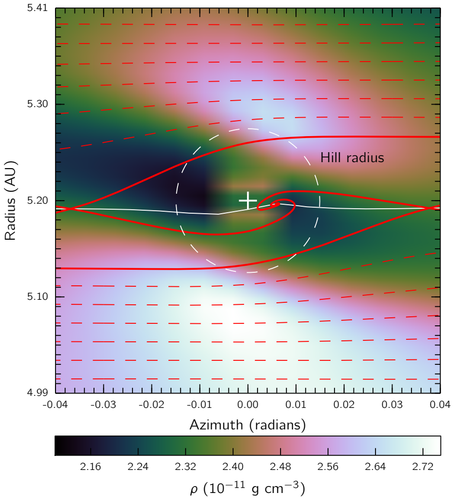
Density in the disk midplane



Net force opposite empty or underdense region

Why is the heating torque positive - 2?

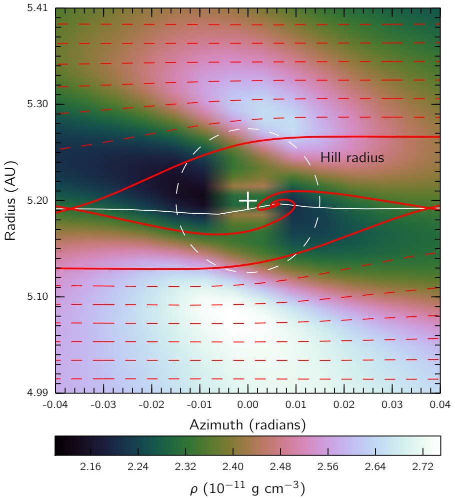
Density in the disk midplane



Rear lobe more pronounced: net force frontward ⇒ positive net torque

Sub-Keplerian disk ⇒ asymmetric lobes

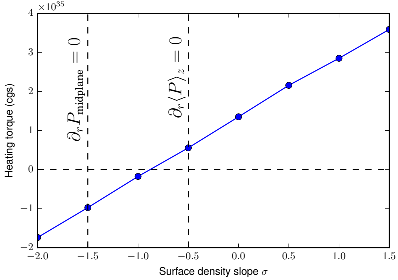
Planet is outside of corotation (white line)



Material from outer disk receives more heat

Sub-Keplerian disk ⇒ asymmetric lobes

Planet is outside of corotation (white line)



Heating torque negative only when disk super-Keplerian

$(\Sigma \propto r^{-\sigma})$

Strong dependence on metallicity

Twofold dependence on metallicity

- through the bombardment rate: scales with amount of solids
- through the opacity: scales with amount of dust

Strong dependence on metallicity

Twofold dependence on metallicity

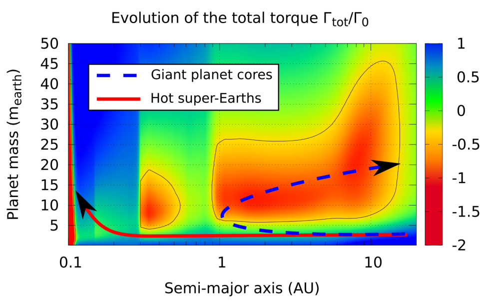
- through the bombardment rate: scales with amount of solids
- through the opacity: scales with amount of dust

Strong dependence on metallicity

Twofold dependence on metallicity

- through the bombardment rate: scales with amount of solids
- through the opacity: scales with amount of dust

Bifurcation depending on system's metallicity



(Cossou et al. '14)

Early Solar System

- Our fiducial calculation has a conservative opacity $\kappa = 1$ cm^2.g^{-1}
- and heating torque largely insensitive to surface density and viscosity

In the early Solar System the most massive embryos should have undergone outward migration (if $\tau \lesssim O(10^5)$ yrs)

Conclusions and perspectives

Conclusions

- Heating torque positive in sub-Keplerian disks
- Increases with accretion rate
- Strongly depends on disk's solid content
- Yields a bifurcation of embryos' migration behavior wrt metallicity

Perspectives

- Conservative estimates (converged): discards inner Hill sphere
- Flow can be complex on a smaller scale (Ormel+ 15, Fung+ 15) $\Rightarrow$ needs AMR
- Relax fixed circular orbit. Potentially impact on e (and i ?)