Planet-disk interaction in dusty disks

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Niels Bohr Institutet

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Can planet migration be affected by the dust component?

- Planet-disk interaction due to the gaseous component has been extensively studied (see Kley & Nelson 12, Baruteau+ 14 for reviews)
- It is clear that dust is ubiquitous in protoplanetary disks
- Dust-to-gas mass ratio usually small ($\sim 1\%$)
- Planet migration scales with the mass of the disk (e.g., Goldreich & Tremaine 1979, ..., Tanaka et al. 2002)

So... Is dust relevant for migration?

...Because the total dust mass is two orders of magnitude lower than the gas, one would expect the migration to be driven by gas and not dust. However, would this really be the case?... (Fouchet+ 07)

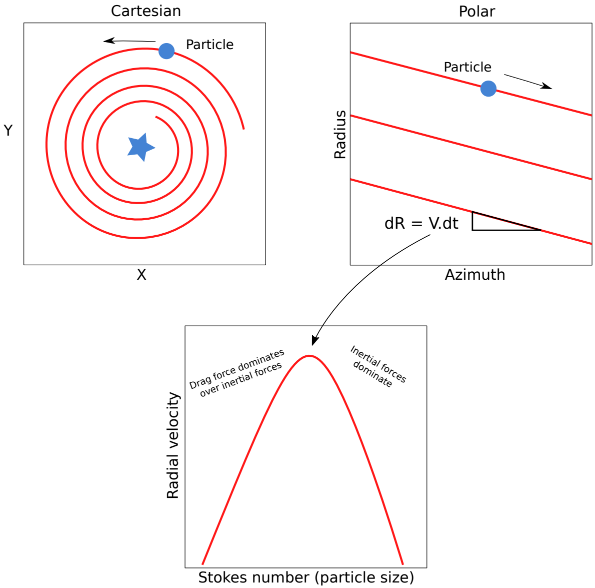
It can be! see e.g., Benítez-Llambay & Pessah 18; Chen & Lin 18; Pierens+ 19; Kanagawa 19.

Flavors of dust-induced torques

- **Heating torque**: *(aka thermal torques). Gravitational energy of accreting solids transformed into heat and released asymmetrically close to the protoplanet* – see Benítez-Llambay+ 15, Masset 17, Masset & Velazco 17 ... Guilera+ 19
  Octavio's talk...
- **Dynamical torques**: *arising from an asymmetric distribution of dust close to the planet* – see Benítez-Llambay & Pessah 18 (low metallicity), Chen & Lin 18, Pierens+ 19 (high metallicity)
- **Feedback induced torques**: *arising from modifications of the gas surface density induced by the dust radial drift* (Kanagawa 19)
- **Planetesimal-driven migration**: *arising from scattering of planetesimals, N-body simulations* – see e.g., Levison+ 10, Capobianco+ 11

Dust dynamics - Radial drift

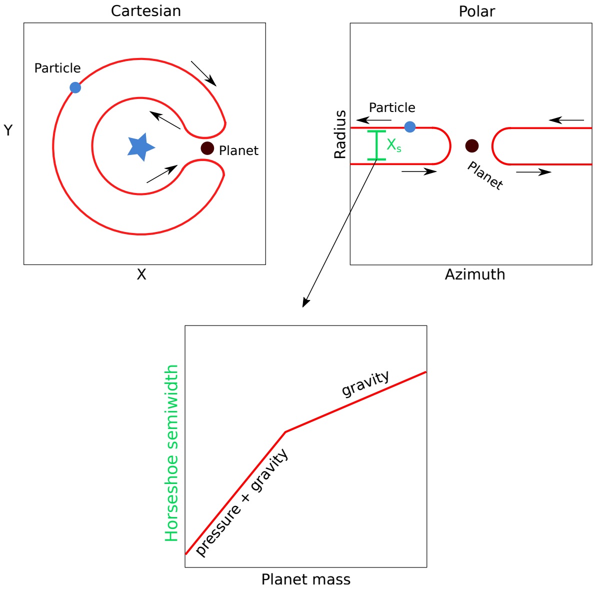
- Gaseous disks are sub-Keplerian (negative pressure gradient)
- Dust is not subject to "intrinsic" pressure gradients
- Dust is subject to a headwind exerted by the gas that removes its angular momentum
- Dust drifts radially
- Drift speed depends on the particle size (+ background gas density, temperature)



see e.g., Safronov 72, Whipple 72, Weidenschilling 77, Nakagawa+ 86

Dust dynamics - Horseshoe motion

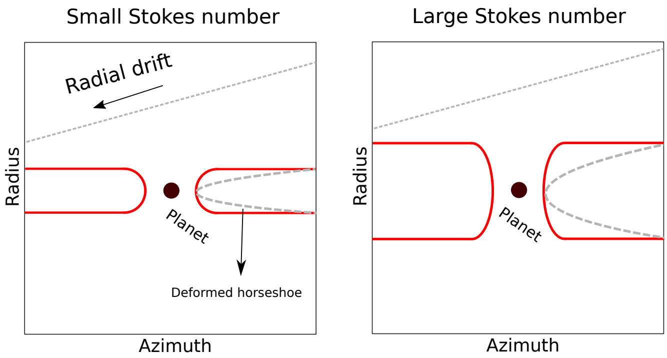
- In the absence of gas, dust particles develop horseshoe motion close to the planet
- The libration time depends on the width of the horseshoe
- Horseshoe width proportional to the Hill Radius (measure of the planet torque)
- For the gas component, it scales differently depending on the planet mass



see e.g., Murray & Dermott 2000, Paardekooper+09

Dust dynamics - Horseshoe motion of dust in presence of gas

$$\frac{d\mathbf{v}_{\mathrm{d}}}{dt} = -\frac{\Omega_{\mathrm{K}}}{\mathcal{S}}\left(\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}}\right) - \nabla\phi_* - \nabla\phi_p$$



For low-mass planets, the **width of the "horseshoe"** depends on the Stokes Number

Two different scaling laws (see Benítez-Llambay & Pessah 18)

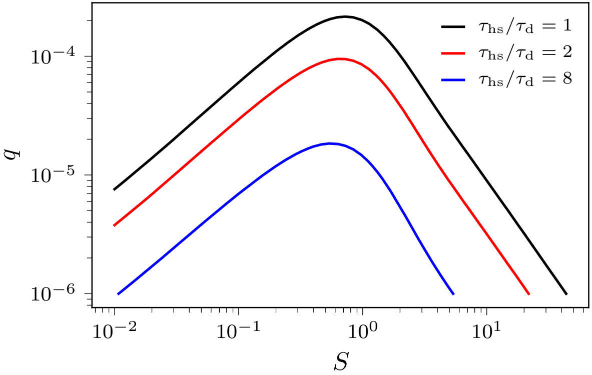
Radial drift + Horseshoe motion (planet torque)

- An important timescale is the horseshoe *libration* time:

$$\tau_{\rm hs} \equiv \frac{2\pi}{\Omega_{\rm p} - \Omega_{\rm hs}} \propto \frac{1}{x_{\rm s}}$$

- The drift timescale:

$$\tau_{\rm d} \equiv \left| \frac{x_{\rm s}}{v_r} \right|$$



For $\tau_{\rm d}$ shorter than $\tau_{\rm hs}$
significant modifications of the horseshoes are expected

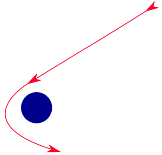
c.f., Dipierro+ 17.

Dust particles + Disk & Planet torques: a simplified picture

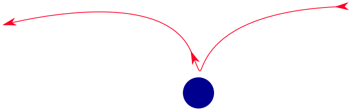
Dust particles drift radially because of a systematic disk torque exerted by the headwind

The planet torque pushes away approaching particles

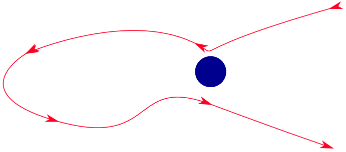
- **Headwind torque larger than planet torque:** dust particles easily cross the horseshoe region



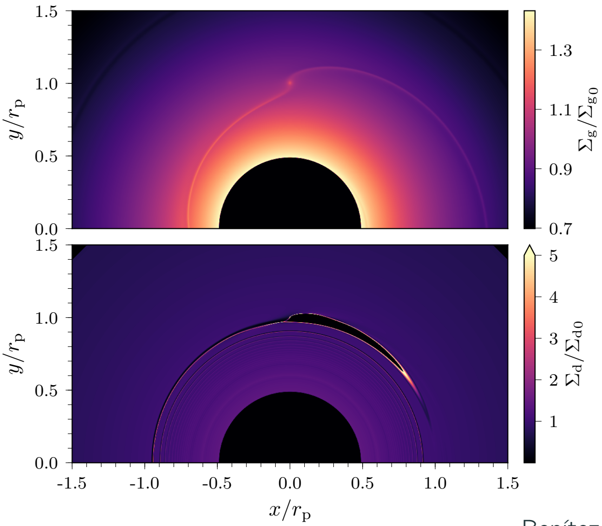
- **Planet torque larger than headwind torque:** particles cannot cross horseshoes (Type II)



- **Planet torque $\sim$ Headwind torque:** the interplay between the planet torque and the headwind torque produces a partial gap (Type III)



Dust-asymmetry example



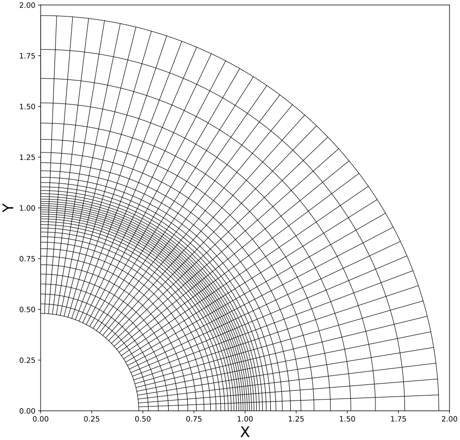
Benítez-Llambay & Pessah 18
also seen in Fouchet+ 07,
Morbidelli & Nesvorny 12,
Dipierro+ 17

Numerical framework

Two-fluid simulations with the multifluid code FARGO3D (Benítez-Llambay+16, 19)

FARGO3D

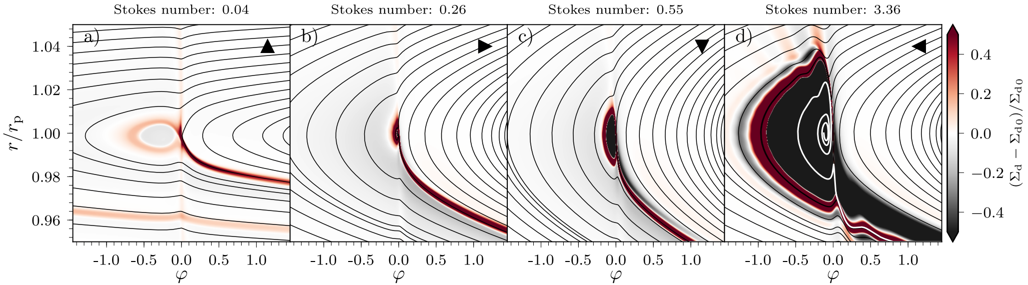
- Versatile Multifluid MHD code with emphasis on PPDs
- Multiple geometries/dimensions
- Runs on clusters of CPUs or GPUs
- Git repository at https://bitbucket.org/fargo3d/public



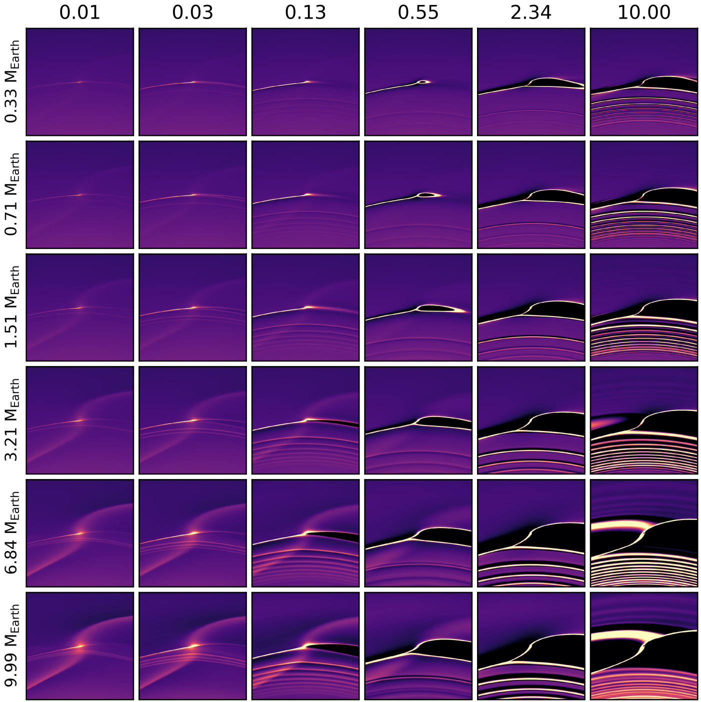
Resolution is important

- Horseshoe region $\propto m_{\mathrm{p}}^{1/2}$
- Pressure scale $\propto H$
- Lindblad resonances (1:2, 2:1 MMRS)
- $n_r \times n_\varphi = 768\text{x}12288$ (180 cells per scale height)

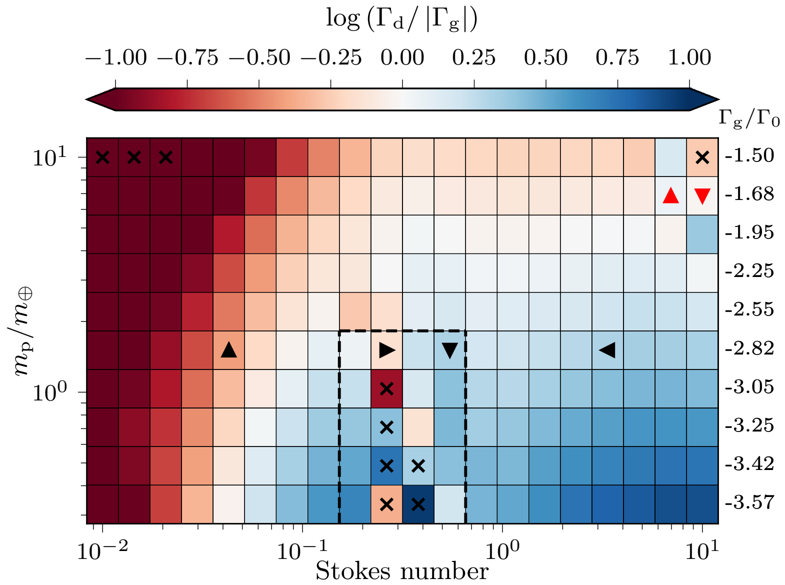
Radial drift + planet torques create asymmetries



Benítez-Llambay & Pessah 18


0.01
0.03
0.13
0.55
2.34
10.00
0.33 M_Earth
0.71 M_Earth
1.51 M_Earth
3.21 M_Earth
6.84 M_Earth
9.99 M_Earth

Torque map



Benítez-Llambay & Pessah 18

Final comments

- Large torques can arise from the dust component if the right conditions are met
- No need of large dust-to-gas mass ratios, just the right planet mass and dust size distribution
- Dust torques can be larger than thermal torques
- Dust torques have the potential to change the migration history of planets
- A realistic assessment of dust torques requires not only realistic models for the dust-size distribution/evolution (at least) close to the planet but also to use different numerical methods (Phantom?)

Dust and its effects should not be neglected when studying planet migration