HOW DO GIANT PLANETARY CORES SHAPE THE DUST DISK?

Giovanni Picogna

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Institut für Astronomie & Astrophysik - Universität Tübingen

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CONTEXT

- dust in the region of active planet formation is visible, so it is a powerful tool to test planet formation models with observations;
- if a planetary core is able to filtrate effectively a range of dust sizes, the formation of terrestrial planets in the inner regions can be affected;
- a giant planet can sustain a long-lived vortex at the outer gap edge, for low viscosities, promoting a second generation of planets;
- a gap in the dust disc can effectively reduce the metallicity of the planetary core;
- the evolution and potential accretion of pebble-like particles on to planetary cores can be very important for giant planet formation (Lambrechts & Johansen, 2012).

AIMS

1. what are the dust accretion rates in the various phases of planet formation?

2. what is the 3D structure of the dust disc interacting with a growing planet?

3. how are multiple giant planetary cores shaping the dust disc?

4. what are the dust sizes effectively filtered by a planet?

MODEL

- Thermal mass

$$M_{\mathrm{th}} = \frac{{\mathrm{c_s}}^3}{\mathrm{G}\Omega_{\mathrm{p}}} = M_\star \left(\frac{H}{R}\right)^3$$

- Thermal criterion

$$M_{\mathrm{p}} > M_{\mathrm{th}} \rightarrow q = \frac{M_{\mathrm{p}}}{M_\star} > \left(\frac{H}{R}\right)^3 = 1.25 \times 10^{-4}$$

- Viscous criterion

$$q \geq \frac{40\nu}{R_{\mathrm{p}}^2 \Omega_{\mathrm{p}}} = 40\alpha_{\mathrm{SS}} \left(\frac{H}{R}\right)^2 = 4 \times 10^{-4}$$

STOPPING TIME

- it quantifies the coupling between the solid and gas components and can be defined as:

$$\mathsf{F}_{\mathrm{D}} = -\frac{1}{\tau_{\mathrm{f}}}\Delta\mathsf{v}_{\mathrm{p}}$$

- or as the non-dimensional stopping time (Stokes number)

$$\tau_{\mathrm{s}} = \tau_{\mathrm{f}}\Omega_{\mathrm{K}} = \frac{s\rho_{\mathrm{s}}}{\rho_{\mathrm{g}}\bar{V}_{\mathrm{th}}}$$

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  - Epstein regime, for $s < \lambda$, the interaction between particles and single gas molecules becomes important
  - Stokes regime, for $s >> \lambda$, particles experience gas as a fluid

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  - Epstein regime, for $s < \lambda$, the interaction between particles and single gas molecules becomes important
  - Stokes regime, for $s >> \lambda$, particles experience gas as a fluid
- we model both regimes with a smooth transition between them (Haghighipour & Boss, 2003; Woitke & Helling, 2003)

NUMERICAL METHODS

- we use 2D FARGO and 3D PLUTO hydro codes
- we introduce a population of partially decoupled particles modeled as Lagrangian particles
- the particles are evolved using semi-implicit (leap-frog like) and fully implicit integrators (Zhu et al. 2014) in cylindrical and spherical coordinates.

HL TAU

THE HL TAU SYSTEM

- An outstandig example of the new data coming from the observations of planet forming regions is the HL TAU system, where axysimmetric ring structures and gaps are visible.
- with our method we scanned the parameter space in order to recreate the observed features

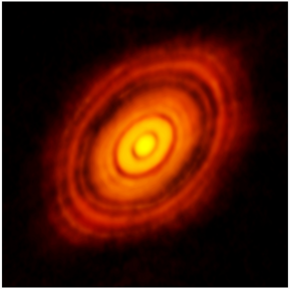

Figure 1: HL TAU system. Source: http://www.eso.org/public/news/eso1436/

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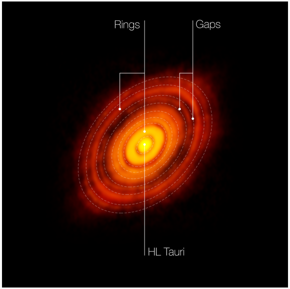
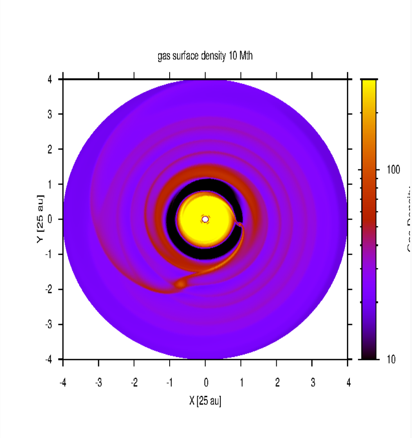


Figure 1: HL TAU system - continuum 233 GHz image. Source: http://www.eso.org/public/news/eso1436/

Physical quantity	Value
Numerical code	FARGO (2D)
Disk mass ($M_\odot$)	0.135
Disk extent (au)	[2.5,100]
Aspect ratio	0.05
Viscosity ($\alpha_{\rm SS}$)	0.004
Surface density profile	-1
Temperature profile	-1
EOS	Isothermal
Dust particles	1×10^6
Dust density (g/cm^3)	2.6
Dust size (cm)	0.1,1,10,100
Star mass ($M_\odot$)	0.55
Planet masses ($M_{\rm th}$)	1,5,10
Planet semi–major axes (au)	25,50

10 THERMAL MASSES

- mm–sized particle evolution (movie)



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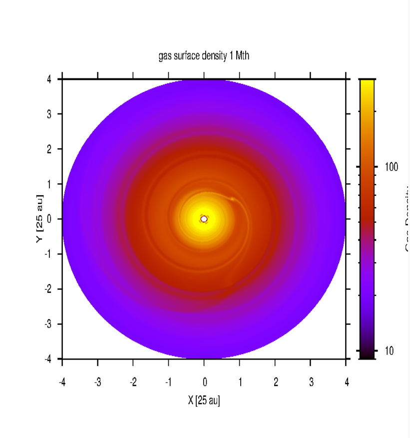
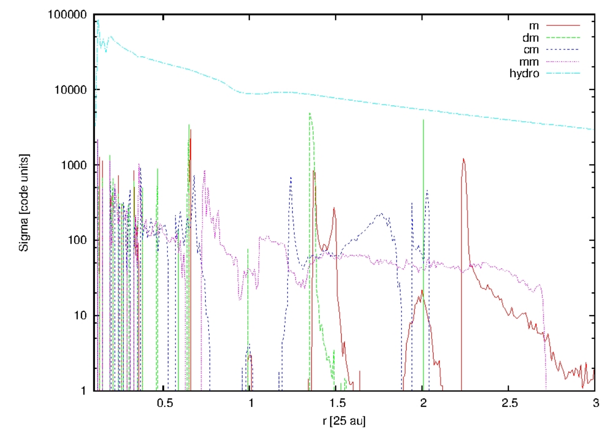
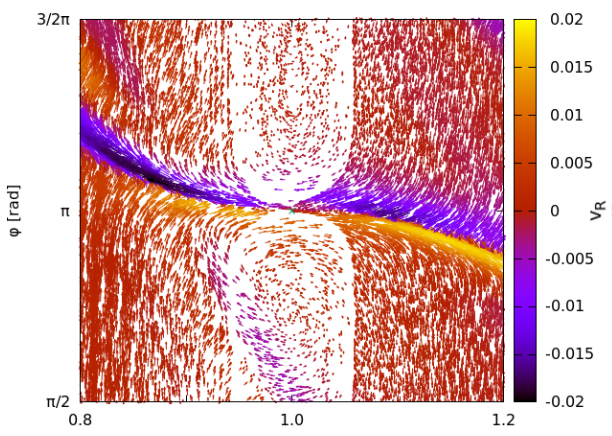


- mm–sized particle evolution (movie)
- the gap is much more clear in the dust disc

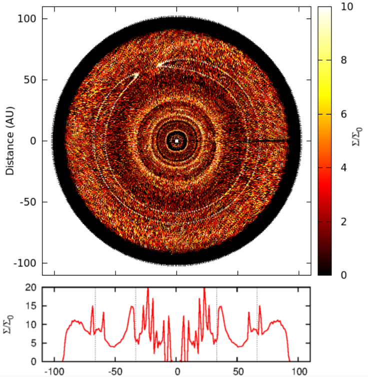


- mm–sized particle evolution (movie)
- the gap is much more clear in the dust disc
- the inner planet is not able to filtrate mm size dust



REALISTIC PLANETARY MASSES

- The best match was obtained with an inner $0.07\,M_{\mathrm{Jup}}$ mass planet and an outer $0.35\,M_{\mathrm{Jup}}$ mass planet (Picogna & Kley, 2015).
- Taking an initial disc mass of 1/10 the original one, we can reobtain the observed gap sizes for 10 and $20\,M_{\oplus}$.



PARTICLE ACCRETION & FILTRATION

Physical quantity	Value
Numerical code	PLUTO (3D)
Disk mass ($M_\odot$)	0.01
Disk extent (au)	[2,13]
Aspect ratio	0.05
Viscosity ($\alpha_{\rm SS}$)	0.001
Surface density profile	-0.5
Temperature profile	-1
EOS	Isothermal
Dust particles	3.2×10^5
Dust density (g/cm^3)	1.
Dust size (cm)	$[10^{-2}, 10^6]$
Star mass ($M_\odot$)	1.0
Planet masses ($M_{\rm th}$)	0.24,2.4
Planet semi–major axes (au)	5.2

100 EARTH MASS PLANET

- dust and gas evolution (movie)

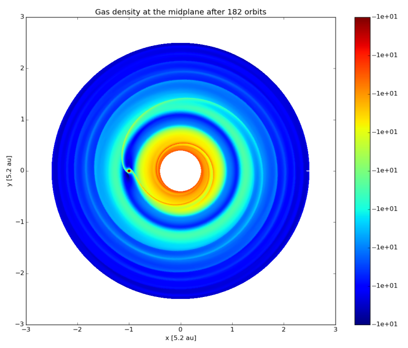


Figure 2: gas density at the midplane after 182 orbits

100 EARTH MASS PLANET

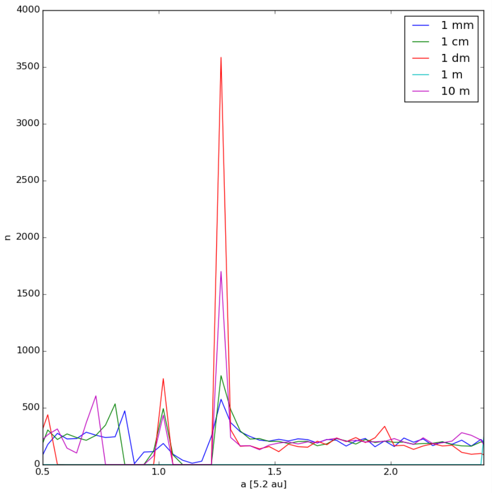


Figure 2: particle gap size

100 EARTH MASS PLANET

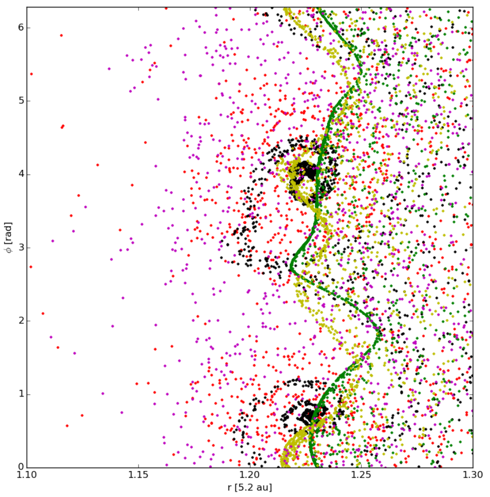


Figure 2: particle vortex for 10 m (green), m (yellow), dm (black), cm (red), mm (violet) particles.

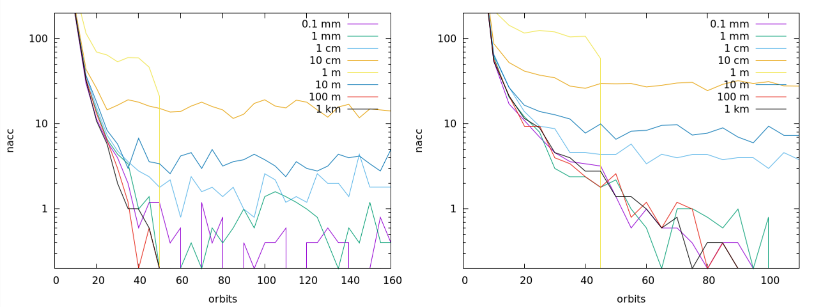


Figure 3: accretion rates for a 100 $M_\oplus$ (left side) and 10 $M_\oplus$ (right side) mass planets.

WHAT'S NEXT?

1. modeling 3D global disc with radiative transport
   - close to the planet location, the temperature can be sufficiently high to ablate and vaporize the dust
2. study the impact of the Vertical Shear Instability
   - the region of active planet formation are supposed to be dead zones, since the ionization level is very low
   - however there are many hydrodynamical instabilities than can occur in these regions and drive the angular momentum transport
   - the most widely applicable instability is the VSI which grows in disc models for which $d\Omega/dZ \neq 0$ and which experience thermal relaxation on dynamical time-scales or shorter (see Nelson et al. 2013, Stoll & Kley, 2014)
   - dust evolution can drastically change in this scenario (movie)

SUMMARY

- dust gaps are wider for higher mass planets and more decoupled particles
- the HL Tau system can be explained by the presence of several massive cores ($0.07M_{\rm Jup}$, $0.35M_{\rm Jup}$) shaping the dust disc
- only a narrow range of dust sizes is captured within the short-lived vortex, for realistic viscosities
- a planet is able to filtrate effectively after a few tens of orbits the particles with stopping time around unity
- the accretion of particles above 100 m and below 1 cm decreases steadily, while dust particles in between keep a steady accretion.

QUESTIONS?

- We adopted the formula by Haghighipour & Boss (2003)

$$\tau_\mathrm{s} = \tau_\mathrm{f}\Omega_\mathrm{K} = \frac{\rho_\bullet a_\bullet}{\rho_\mathrm{g}}\left[(1-f)\bar{v}_\mathrm{th} + \frac{3}{8}fC_\mathrm{D}v_\mathrm{rel}\right]^{-1}\Omega_\mathrm{K}$$

$$\mathbf{F}_\mathrm{D} = -\frac{1}{\tau_\mathrm{f}}\Delta\mathbf{v}_\mathrm{p}$$

- and the one by Woitke & Helling (2003), Lyra et al. (2009)

$$C_\mathrm{D} = \frac{9\mathrm{Kn}^2 C_\mathrm{D}^\mathrm{Eps} + C_\mathrm{D}^\mathrm{Stk}}{(3\mathrm{Kn}+1)^2}$$

$$C_\mathrm{D}^\mathrm{Eps} \simeq 2\sqrt{1+\frac{128}{9\pi\mathrm{Ma}^2}}, \quad C_\mathrm{D}^\mathrm{Stk} = \begin{cases} 24/\mathrm{Re} + 3.6\mathrm{Re}^{-0.313} & \text{if } \mathrm{Re} \le 500 \\ 9.5\cdot 10^{-5}\mathrm{Re}^{1.397} & \text{if } 500 < \mathrm{Re} \le 1500 \\ 2.61 & \text{if } \mathrm{Re} > 1500 \end{cases}$$

Zhu, Z., Stone, J. M., Rafikov, R. R., & Bai, X.-n. 2014, ApJ, 785, 122