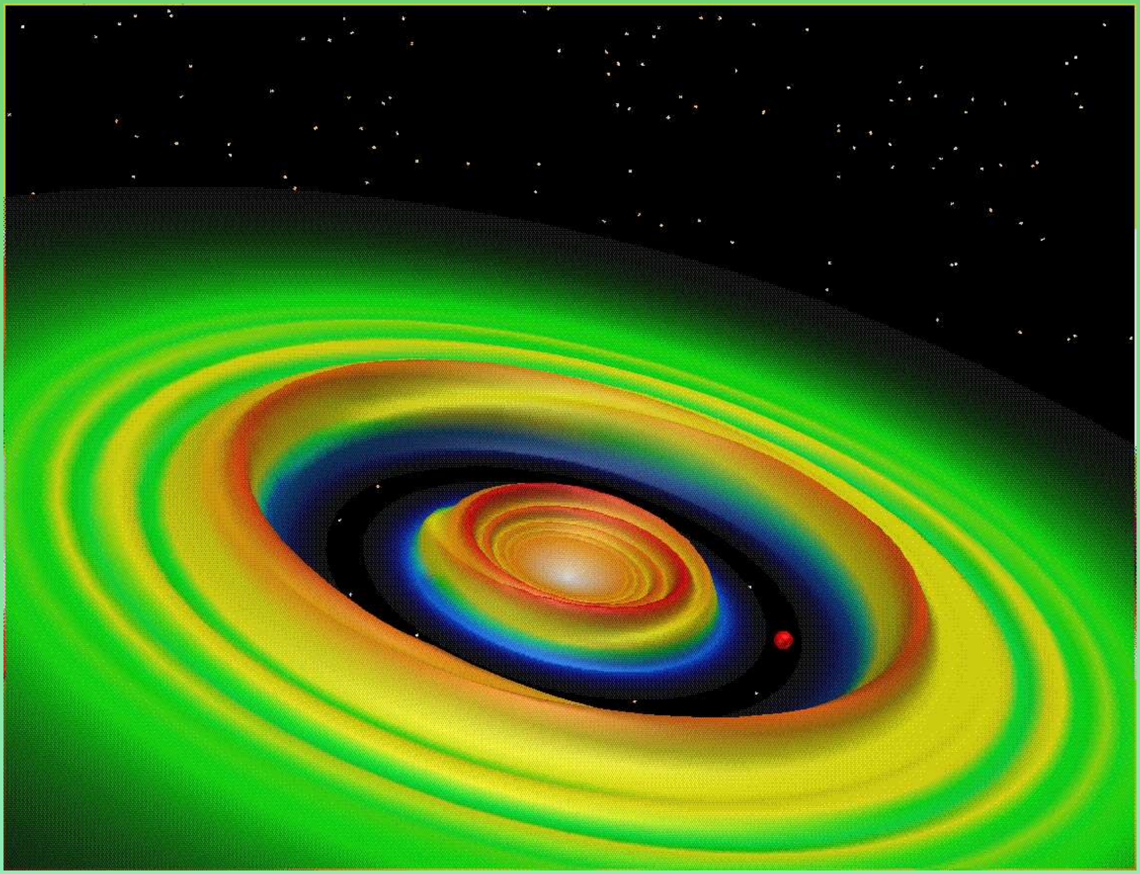
Planets opening dust gaps in gas disks

(Paardekooper, S.-J., Mellema, G., 2004, A&A, 425, L9)



Bryden et al. (1999)

Outline:

1 Gaps in PP-disks

2 Gas-dust interaction

3 Dust gaps

Disk-planet interaction

Influence to the disk

- gaps (a low-density annular region along the planet's path)
- inner holes
- spiral wave patterns, emanating from the Lagrangian points
- warp, shadowed regions, . . .

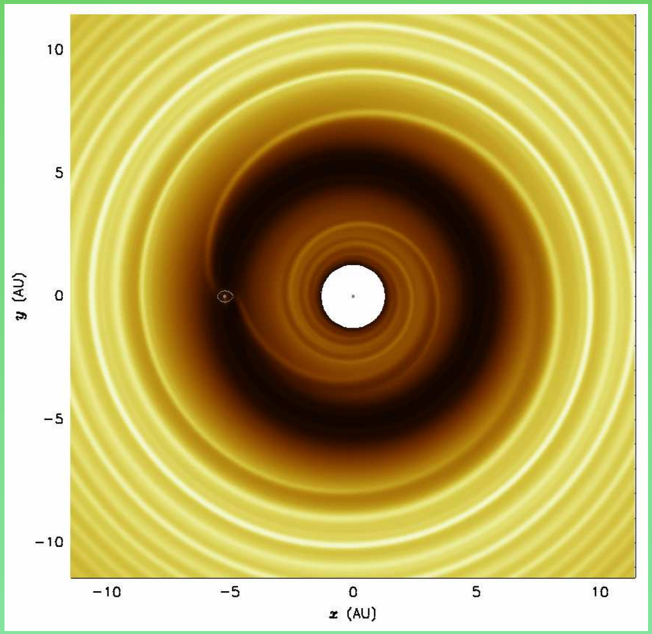
Influence to the planet

- migration:
  - ▷ *type I*, $\sim 10^4$ *yr, (no gap)*
  - ▷ *type II*, $\sim 10^5$ *yr, (inside a gap)*
  - ▷ *type III*, $\sim 10^2 - 10^3$ *yr, (interaction with corrotational flows)*
- eccentricity evolution
- accretion onto the planet

Gap formation

Mechanism:

- giant planet excites tidal perturbations
- trailing shocks are formed
- angular momentum transport in shocks
- material moves away from the planet



Kley (1999)

Gap can be opened if

- planet mass is high enough ($\sim M_J$)
- viscosity is low enough

Gap opening conditions 1

Viscous condition: $t_{\text{open}} < t_{\text{close}}$

opening time: $t_{\text{open}} \simeq \Delta H / T$

$$\Delta H \simeq \Sigma\Omega(r\Delta r)^2$$

(angular momentum needed to open the gap)

Σ . . . disk surface density Ω . . . angular rotational velocity
r_0 . . . radius of the gap Δr . . . gap radial thickness

$$T \simeq r_0^4 \Omega^2 \Sigma q^2$$

(torque due to interaction with spiral waves)

$q \equiv M_p/M_*$ . . . planet-to-star mass ratio

closing time: $t_{\text{close}} \simeq (\Delta r)^2/\nu$

$$\boxed{q > q_\nu \equiv \left(\frac{\nu}{\Omega r^2}\right)^{1/2}}$$

ν . . . kinematical viscosity

Gap opening conditions 2

Thermal condition:

$$H < R_R = \left(\frac{q}{3}\right)^{1/3} r_0$$

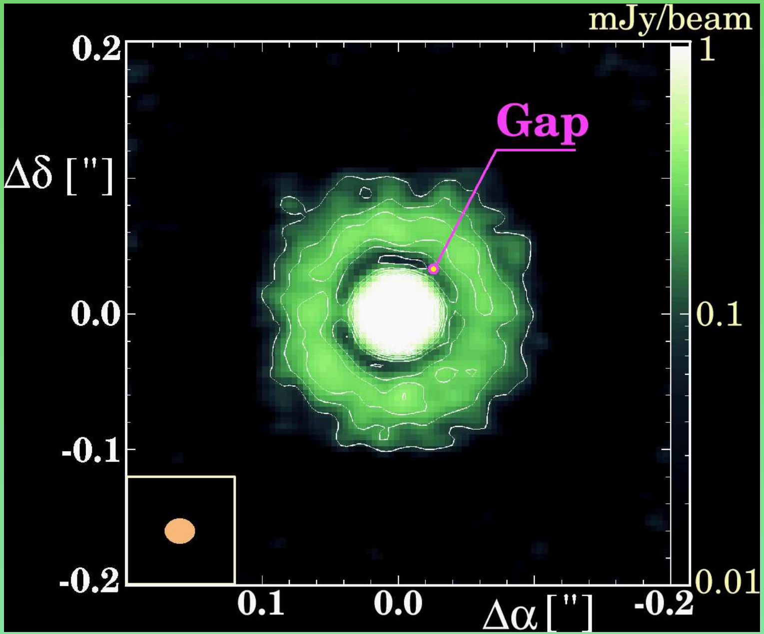
H	$\ldots$	disk semi-thickness
R_R	$\ldots$	Roche radius

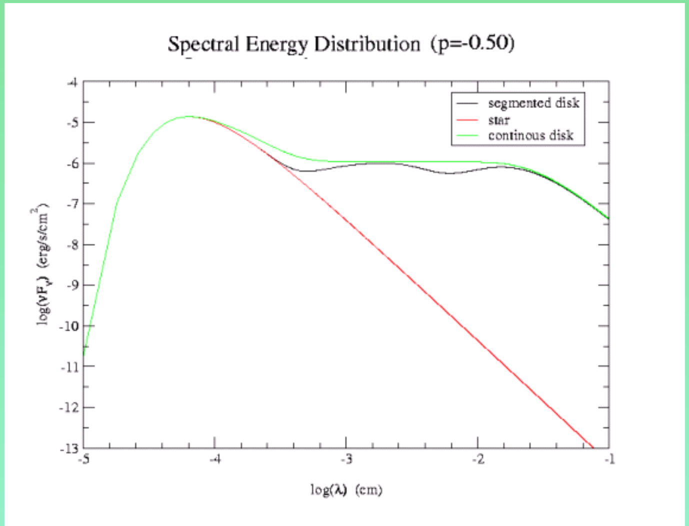
$$q > q_H \equiv 3\left(\frac{H}{r}\right)^3$$

Observations of gaps

IR and submm interferometry:

ALMA will be able to detect gap at 5.2 AU created by 1 Jupiter mass planet at 140 pc (Taurus SF region)
`Wolf et al. (2002)`





IR and submm spectroscopy:

Gaps in spectrum indistinguishable from other features caused by specific dust properties (like absence of specific dust material)
`Steinecker & Henning, 2003`

Dust-gas interaction

- gas and dust have different orbital velocities ⇒ drag force (dust grains spiral inwards)
- for the case where
  - ▷ *sizes of grains are much smaller than the molecular mean free path*
  - ▷ *relative velocity of dust and gas is much smaller than the local sound speed*

Epstein law:

$$\boxed{F_d = \frac{4\pi}{3} a^2 \rho_g c_s (v_g - v_d)}$$

a	. . .	grain sizes	v_g	. . .	gas velocity
ρ_g	. . .	gas density	v_d	. . .	dust velocity
c_s	. . .	local sound speed			

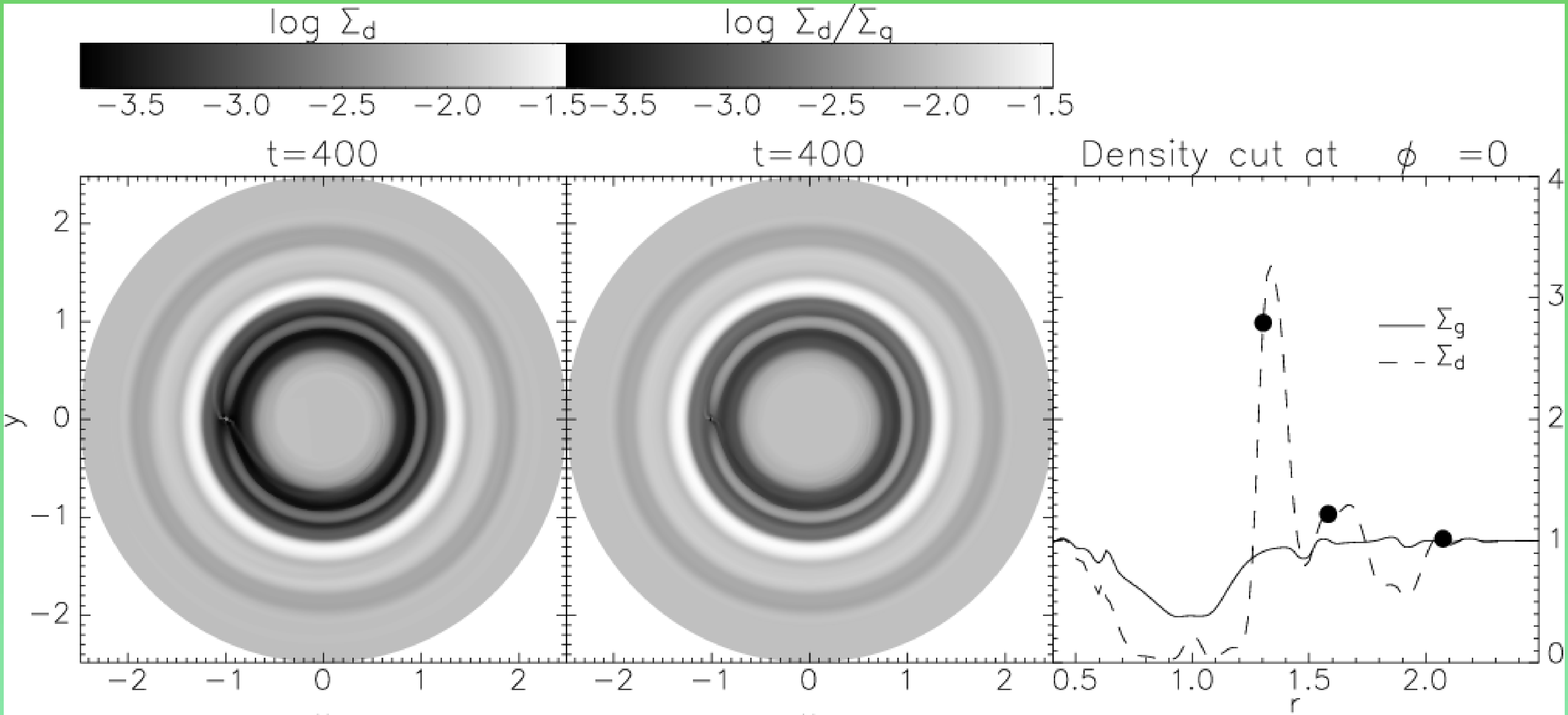
Numerical model

- 2^{nd} order Eulerian HD code, approximate Riemann solver
- 2D cylindrical coordinate frame (r, ϕ)
- two fluids: gas and dust (pressureless), interaction through drag forces
- isothermal equation of state: $p = \Sigma c_s^2$, $c_s = \frac{H}{r} v_{\mathrm{K}}$

Parameters:

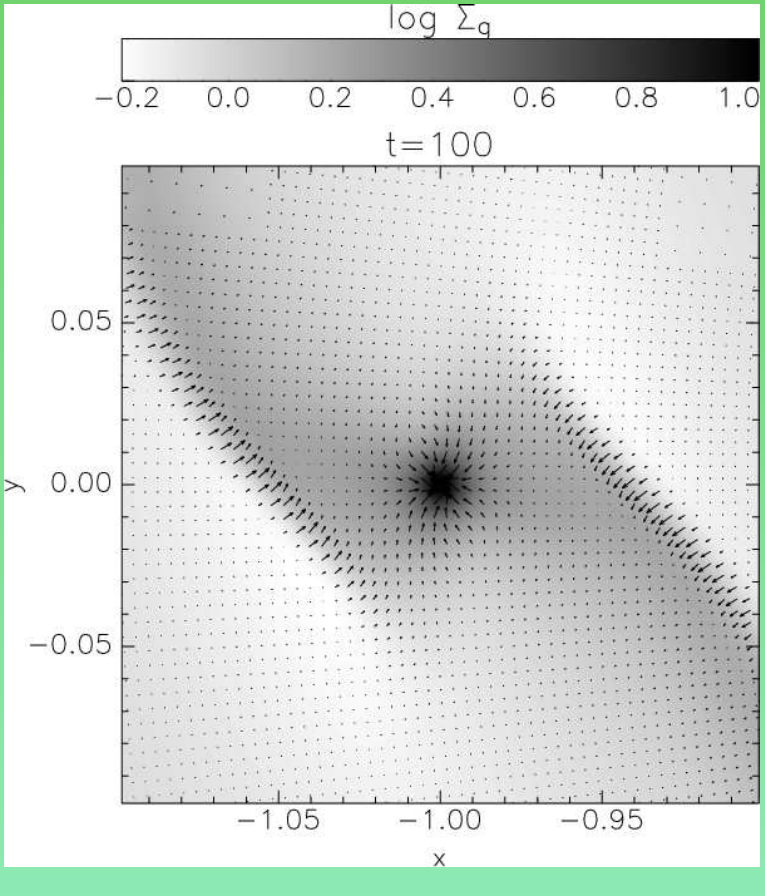
- basic grid 128×384
- $\Sigma_0 = 34$ g cm^{-2} $\leftrightarrow$ $M_{\mathrm{disk}} = 0.01 \mathrm{M}_\odot$ within 100 AU
- $\nu =$const $\leftrightarrow$ $\alpha = 0.004$ at $r = 1$
- $M_p = 0.1 \mathrm{M_J}$ ($0.001 - 0.5 \mathrm{M_J}$ tested)
- dust particle size: $1 \mathrm{mm}$, initial dust/gas mass ratio: 0.01

Formation of dust gap



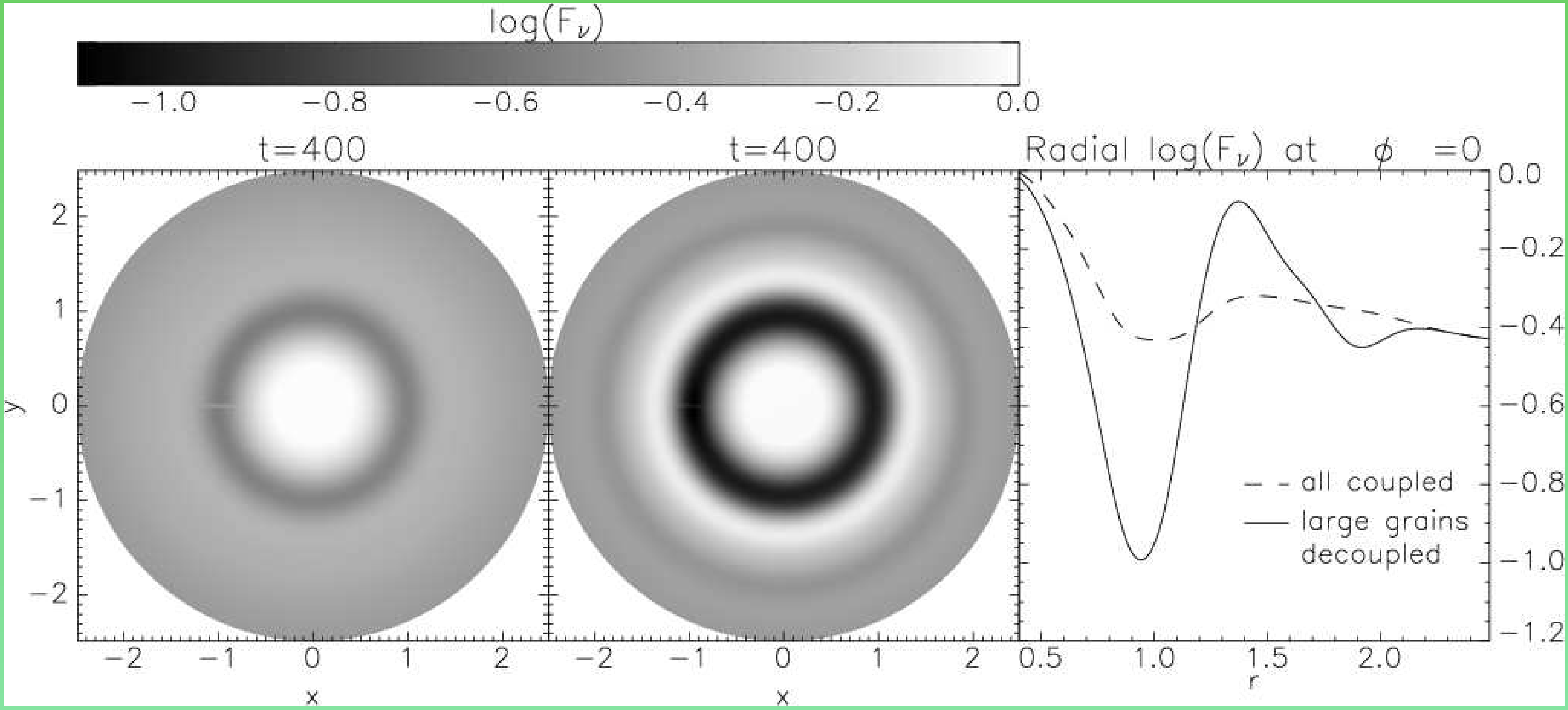
- gap in dust particles, but not in the gas
- dense dust rings at mean 3:2, 2:1 and 3:1 mean motion resonances
- small density bump at corotation ($r = 1$)

Formation of dust gap - mechanism



- dust decouples from gas near the spiral shocks
- dust do not feel the shock directly
- larger flux of dust particles into spiral waves
- spiral waves remove material away ⇒ more efficient depletion of dust from the gap
- works for $M_p > 0.05\mathrm{M_J}$ and $a > 0.1\mathrm{mm}$
- particles at higher radii trapped in mean motion resonances
- Kuiper Belt Objects tend to accumulate at the 3:2 and 2:1 mean motion resonances with Neptune (`Luu & Jewitt, 2002`)

Simulated observations by ALMA



- distribution of particle size (`Mathis et al., 1977`), size-dependent opacity (`Miyake & Nakagawa, 1993`) ⇒ flux at $1\mathrm{mm}$ wavelength, $r_0 = 5.2\mathrm{AU}$, $d = 140\mathrm{pc}$, resolution: $12\mathrm{mas}$
- flux density contrast enhanced from ~ 2 to ~ 10

Conclusions

- spiral shocks near the planet are able to decouple larger ($> 0.1\mathrm{mm}$) particles from the gas
- formation of the annular gap in the dust, even if there is no gap in the gas
- minimum planet mass to open the dust gap $\sim 0.05\mathrm{M_J}$
- dust particles may be trapped in mean motion resonances and form dense rings

References

Goldreich, P., Tremaine, S., 1980, ApJ, 241, 425
Kley, W., 1999, MNRAS, 303, 696
Bryden, G., Chen, X., Lin, D. N. C., Nelson, R. P., Papaloizou, J. C. B., 1997, ApJ, 514, 344
Luu, J. X., Jewitt, D. C., 2002, ARA&A, 40, 63
Mathis, J. S., Rumpl, W., Nordsieck, K. H., 1977, ApJ, 217, 425
Myiake, K., Nakgawa, Y., 1993, Icarus, 106, 20
Paardekooper, S.-J., Mellema, G., 2004, A&A, 425, L9
Steinacker, J., Henning, Th., 2003, ApJ, 583, L35
Wolf, S., Gueth, F., Henning, Th., Kley, W., 2002, ApJ, 566, L97