2D models of layered protoplanetary discs

(R. Wünsch, H. Klahr, M. Różyczka, A. Gawryszczak)

R. Wünsch, H. Klahr and M. Różyczka, 2005, MNRAS, 362, 361
The ring instability

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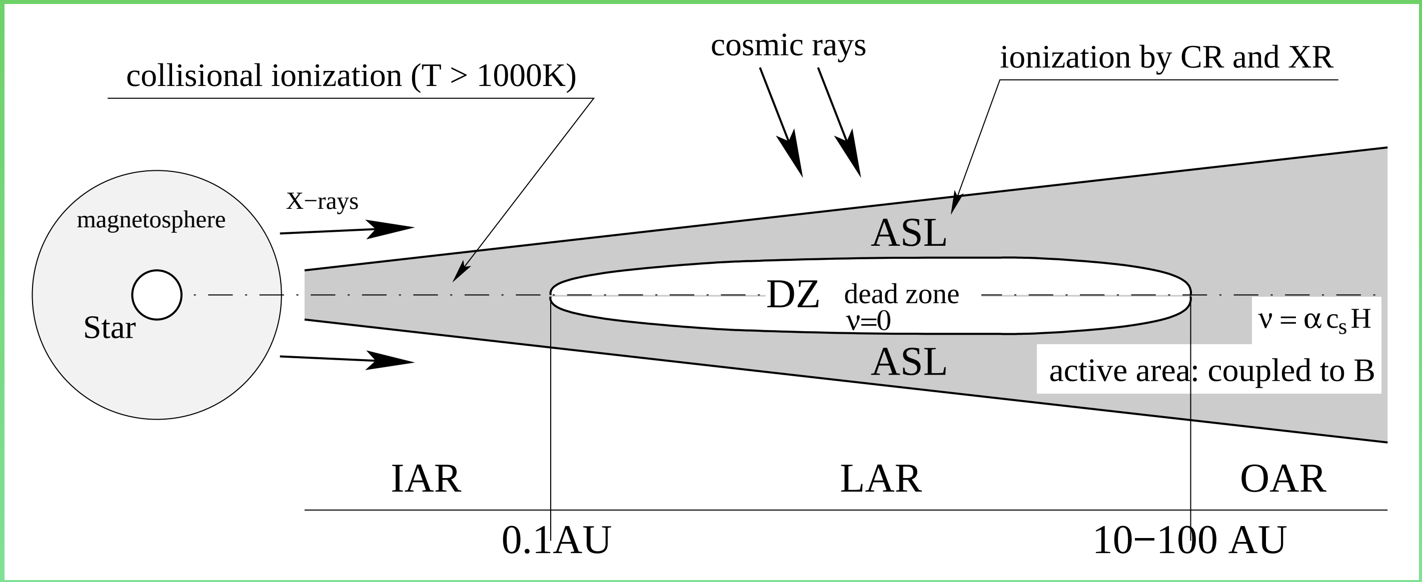
The effect of a residual viscosity in the dead zone

The fate of late planets

(R. P. Nelson, R. Wünsch, M. Różyczka)

Layered-disc: basic idea (Gammie, 1996)



- MRI does not operate in regions with low ionization - dead zone
- ionization sources: particle collisions (T > 1000K), cosmic rays & X-rays (surface layers ~ 100 g cm^{-2})
- disc structure: IAR, LAR ($= 2\times$ASL + DZ), OAR
- in LAR: $\dot{M} = \dot{M}(r) \Rightarrow$ mass accumulation in the dead zone

$$\dot{\Sigma}_{\rm DZ} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$$

Numerical model

- based on RHD code TRAMP: (Klahr et al., 1999)
- radiation transfer: flux limited diffusion approximation
- 2D axially symmetric in spherical (r, θ) coords.
- viscosity:

  $\alpha_a = 10^{-2}$

  (surface layers:

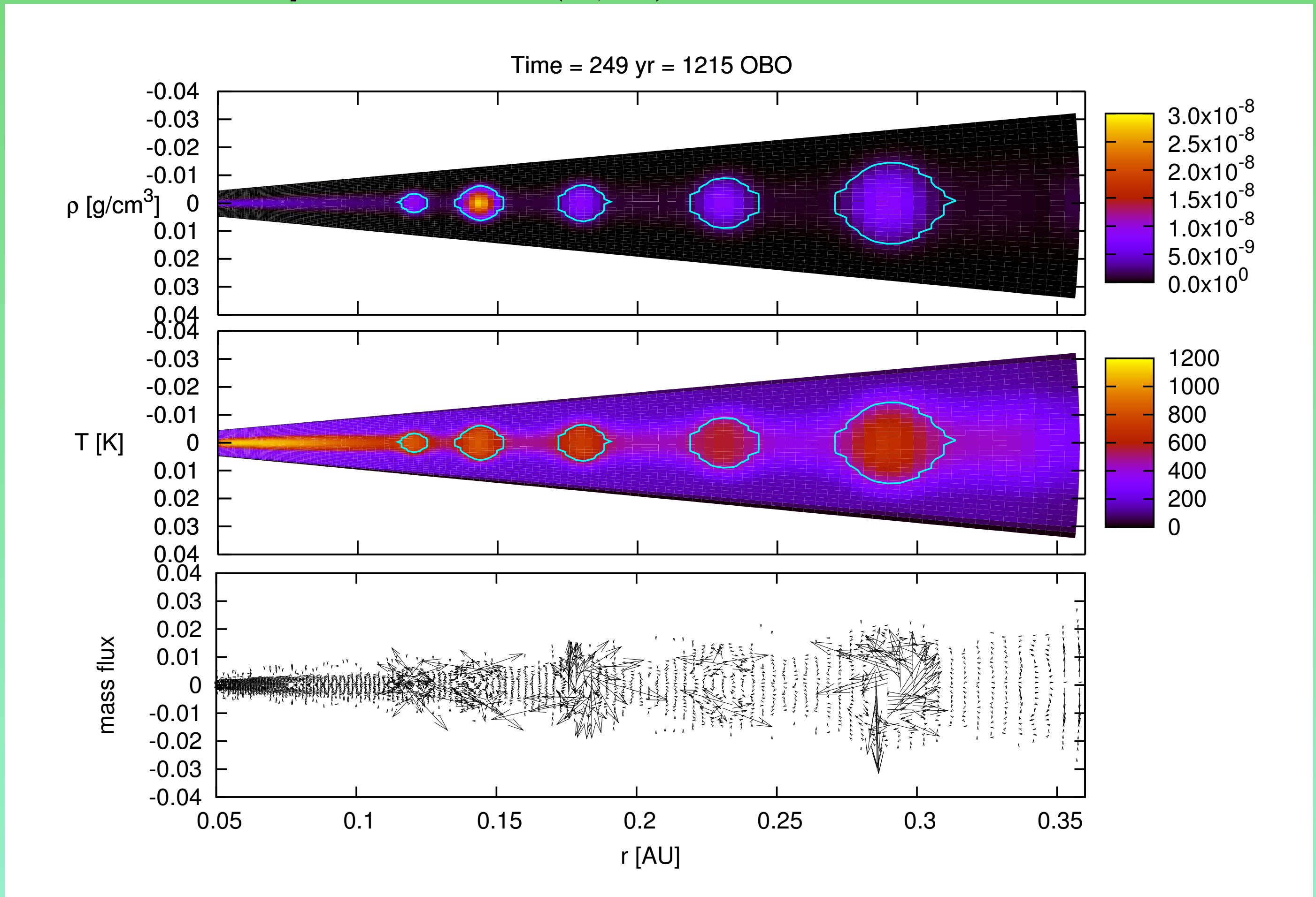
  $\Sigma_a = 100 \mathrm{g\,cm}^{-2}$

  and inner region:

  $T > 1000\mathrm{K}$)

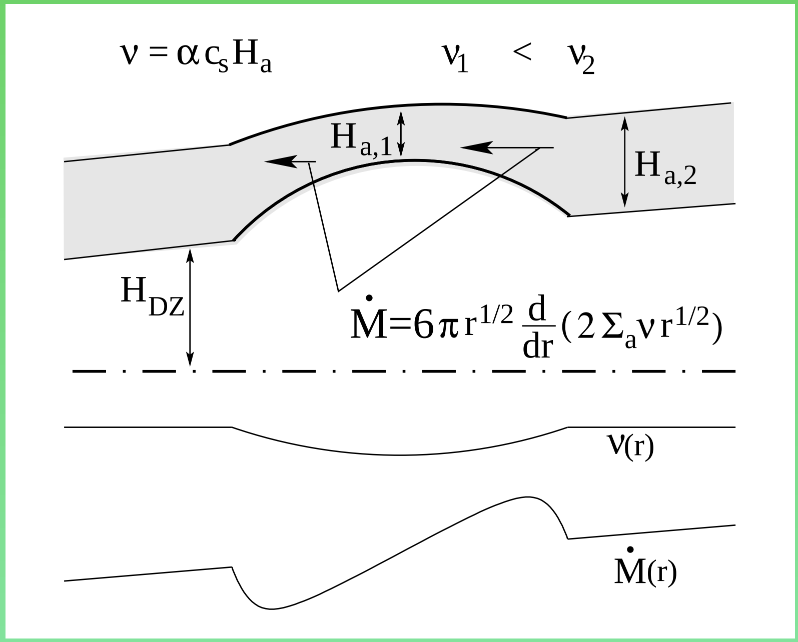
  $\alpha_{DZ} = 0, 10^{-4}, 10^{-3}$

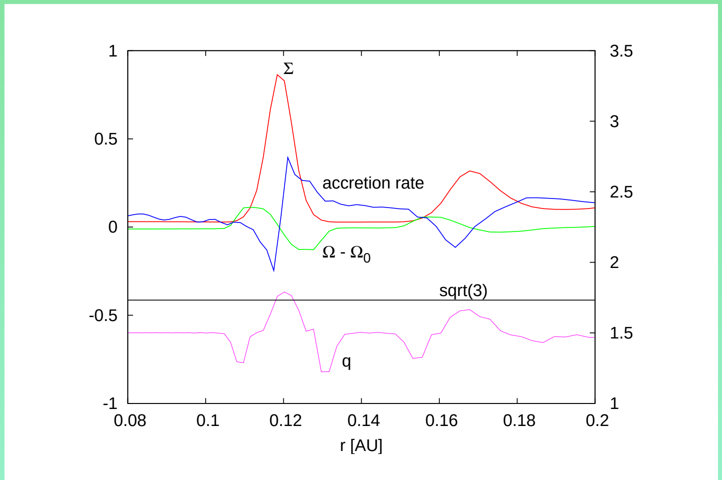
  (elsewhere - dead zone)
- rings formed!



Ring instability - mechanism

- dead zone decomposes into rings
- ring instability mechanism:
  - ▷ *thickness of surface layer* H_a *depends on the dead zone thickness* H_{DZ} *(due to different vertical gravity)*
  - ▷ H_a *is smaller in the ring-like perturbation* $\Rightarrow \nu$ *is smaller there, too*
  - ▷ $\dot{M}$ *depends on derivative of* $\nu \Rightarrow$ *it is smaller in inner edge and higher in outer edge of the ring*
  - ▷ *enhanced mass accumulation in the ring* $\Rightarrow$ *positive feedback*





- rings may work as traps for the dust $\rightarrow$ formation of planets
- rings may decay due to the hydrodynamic instability, if $q > \sqrt{3}$ $(\Omega \sim r^{-q})$

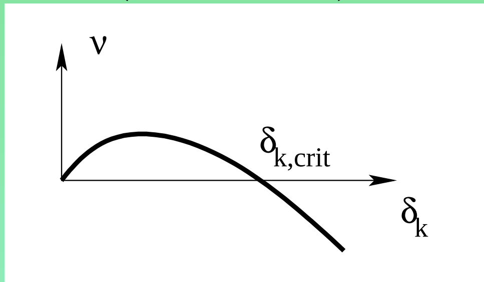
(Papaloizou & Pringle, 1985)

Ring instability - influence of irradiation

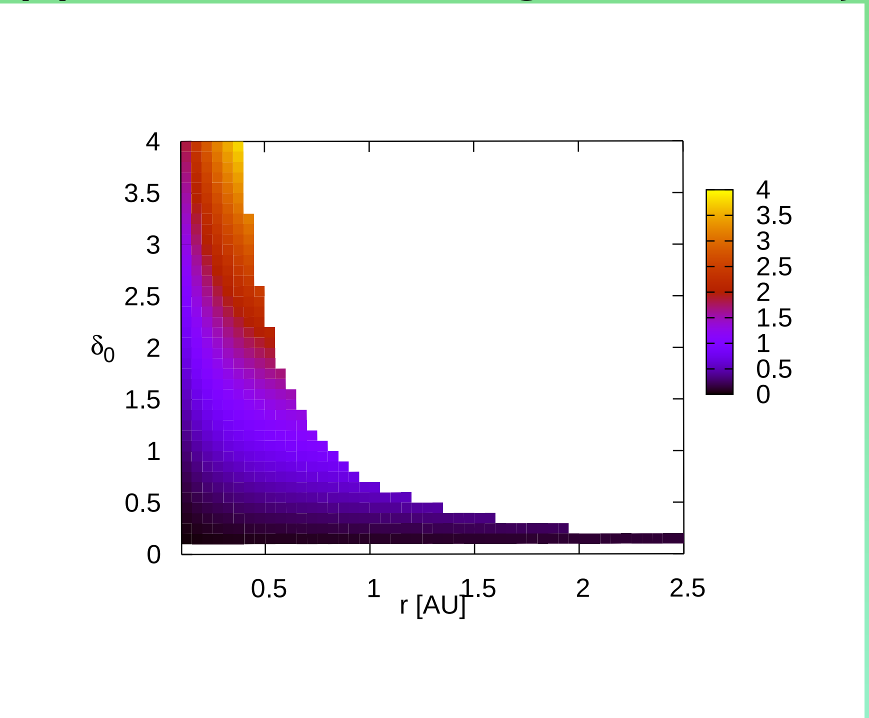
analytical approximative approach: $T_i^4 = \frac{3}{8}\tau T_e^4 + W T_\star^4$

- changes the vertical structure of the unperturbed disc
  - ▷ *conical disc:* $W = \frac{2}{3\pi}\left(\frac{R_\star}{r}\right)^3$ → *viscous term always dominates*
  - ▷ *flaring disc:* $W = \alpha_{\rm gr}\left(\frac{R_\star}{r}\right)^2$, *for* $H/r \sim r^{2/7}$
    → *irradiation important for* $r > 10$ *AU*

- smoothes the temperature ⇒ suppresses the ring instability
  - ▷ *grazing angle of the inner edge of the ring:* $\alpha_{\rm gr} \sim \frac{\delta_k}{l(\delta_0+\delta_k)} + \frac{2}{3\pi}\frac{R_\star}{r}$
    → $\nu(\delta_k, \delta_0, r, l)$



  - ▷ *perturbation of the disc thickness has to reach a certain value, then the instability can grow*



Viscosity in the dead zone - motivation

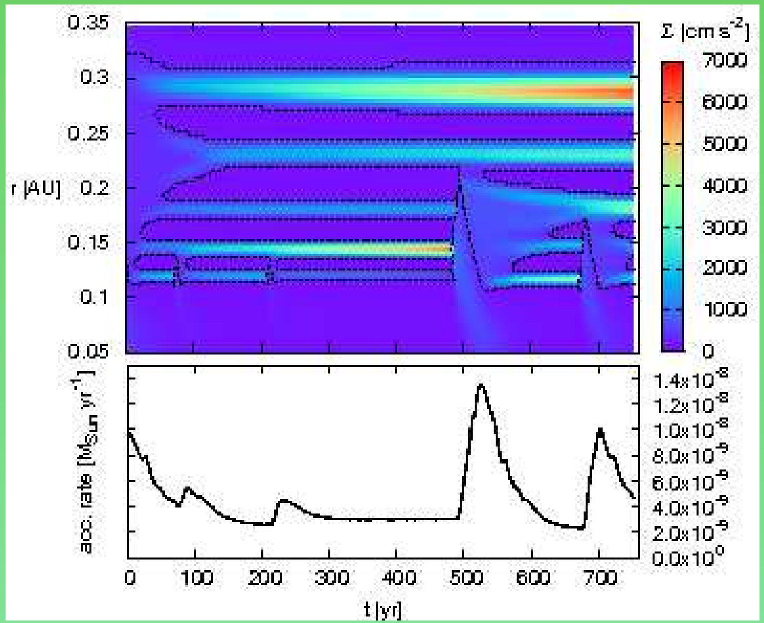
- indications for a small viscosity in the dead zone
  $\longrightarrow$ the undead zone
- caused by purely hydrodynamic turbulence excited by waves propagating from MRI-active surface layers
  (Fleming & Stone, 2003)
- viscosity in DZ $\sim 10\%$ viscosity in active parts

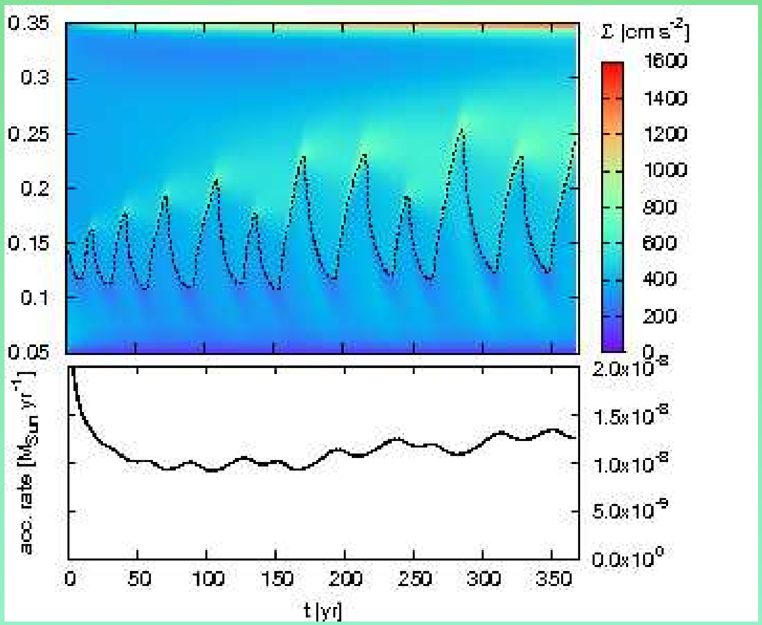
Our models

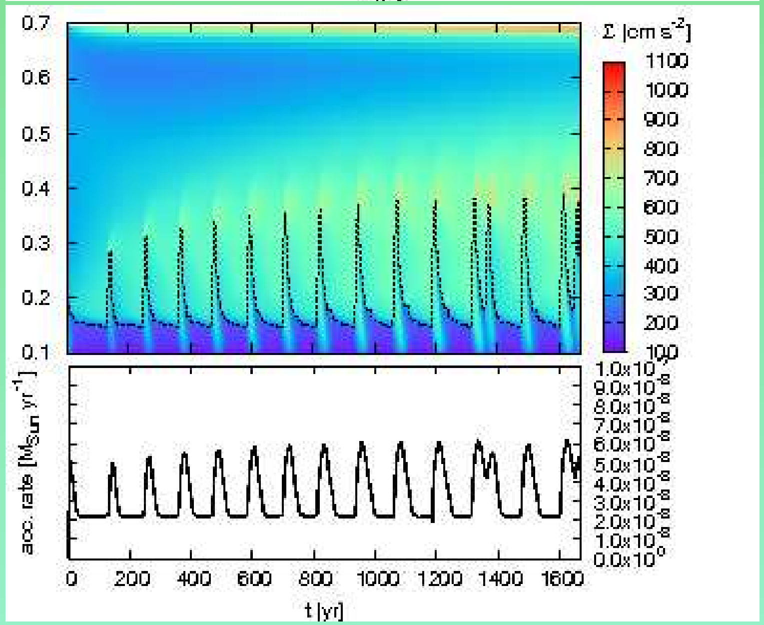
- models with different ν computed for several 1000 orb.:
  - ▷ *definition of* ν: $\nu = \alpha c_s H_a$ *vs.* $\nu = \alpha c_s^2/\Omega$
  - ▷ *viscosity in active parts* $\alpha_a = 0.005, 0.01, 0.02$
  - ▷ *viscosity in the dead zone* $\alpha_{\rm DZ} = 0, 0.01$ *and* $0.1\alpha_a$

Results - minioutbursts

- rings growth rate cca $10\times$ faster for $\nu = \alpha c_s H_a$
- $\alpha_{\rm DZ} = 0, 0.01\alpha_a$ → rings, $\alpha_{\rm DZ} = 0.1\alpha_a$ → mini-outbursts
- high viscosity ($\alpha_a = 0.02$) → regular narrow mini-outbursts, outer part of DZ stationary







Layered disc with $\alpha_{\rm DZ} \neq 0$

- analytical description of layered disc with $\alpha_{\rm DZ} \neq 0$:

$$\dot{M} = 12\pi r^{1/2}\frac{\partial r}{\partial}(\nu_a\Sigma_a + \nu_{\rm DZ}\Sigma_{\rm DZ}), \qquad T_m^4 = \frac{3}{8}\kappa T_e^4\frac{\alpha_a\Sigma_a^2+\alpha_{\rm DZ}\Sigma_{\rm DZ}(\Sigma_{\rm DZ}+2\Sigma_a)}{\alpha_a\Sigma_a+\alpha_{\rm DZ}\Sigma_{\rm DZ}}$$

$$T_e^4 = \frac{9}{4\sigma}\Omega^2(\nu_a\Sigma_a + \nu_{\rm DZ}\Sigma_{\rm DZ})$$

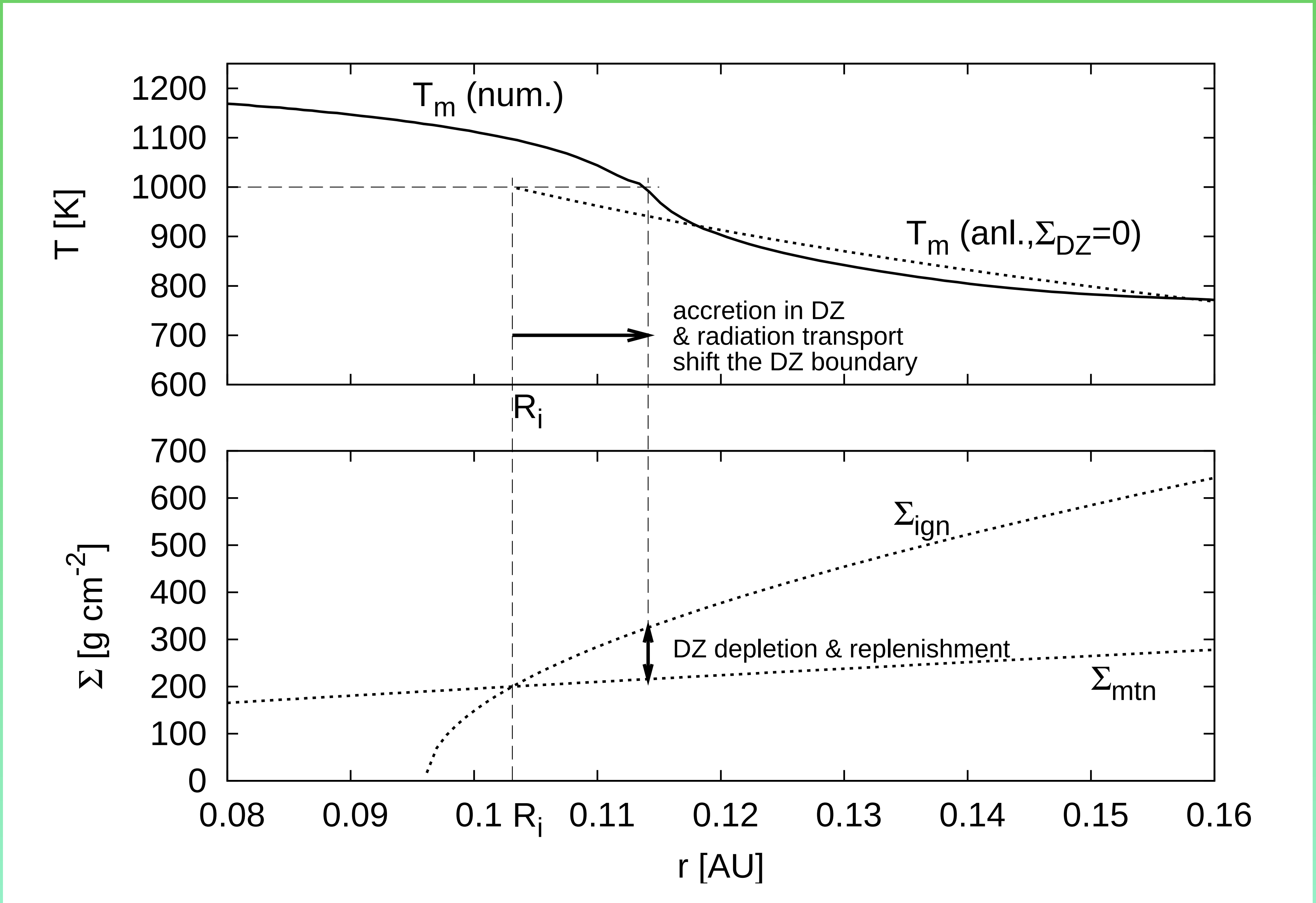
- mid-plane temperature T_m depends on the surface density $\Sigma = 2(\Sigma_a + \Sigma_{\rm DZ})$ (contrary to LD with $\alpha_{\rm DZ} = 0$)
- ignition surface density

$$\Sigma_{\rm ign} = 2\left(\frac{320\sigma}{27}\frac{\mu m_{\rm H}}{k_{\rm B}\Omega\alpha_{\rm DZ}}T_{\rm lim}^{5/2} - \frac{\alpha_a-\alpha_{\rm DZ}}{\alpha_{\rm DZ}}\Sigma_a^2\right)^{1/2}$$

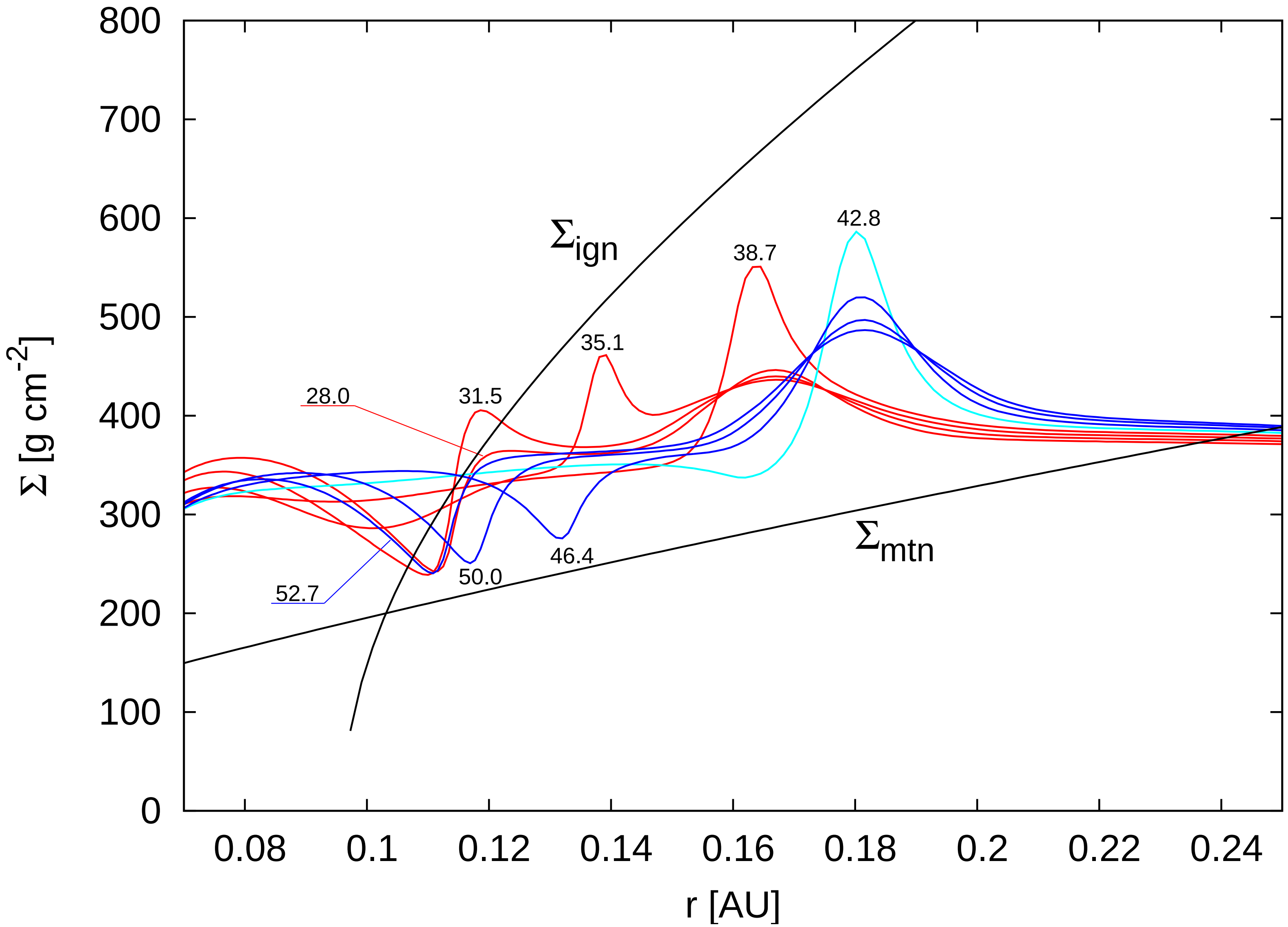
- surface density necessary to maintain the disc active

$$\Sigma_{\rm mtn} = \left(\frac{1280\sigma\mu m_{\rm H}}{27k_{\rm B}\alpha_a\Omega}\right)^{1/2}T_{\rm lim}^{5/4}$$

Mini-outbursts - mechanism



Evolution of one outburst

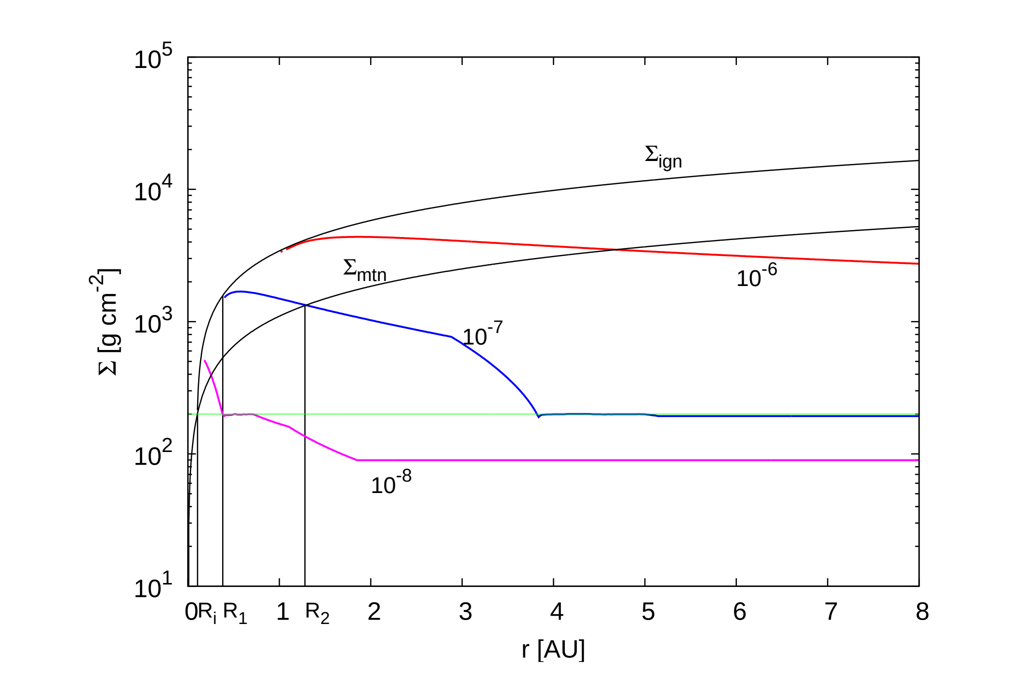


Stationary states

- we search for stationary surface density profiles using 1D code similar to Stepinski (1999) or Armitage et al. (2001)
- numerically solve equation $\dot{\Sigma} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$
- determines T_m from Σ, decides if LD or αD, computes $\dot{M}$, advects mass between cells

  - ▷ *stationary solution exist above* R_1
  - ▷ *part of DZ between* R_1 *and* R_2 *can be ignited externally*
  - ▷ *it contains mass*

$$2.0 \times 10^{-7} \mathrm{M}_\odot \text{ for } \dot{M} = 10^{-8}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$
$$2.7 \times 10^{-4} \mathrm{M}_\odot \text{ for } \dot{M} = 10^{-7}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$
$$0.01 \mathrm{M}_\odot \text{ for } \dot{M} = 10^{-6}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$



Conclusions

- no (or very small) viscosity in DZ $\Rightarrow$ ring instability
- $\alpha_{\mathrm{DZ}} \neq 0 \Rightarrow$ the oscillations of the inner edge of DZ
- stationary accretion ($\dot{M} = \mathrm{const}$) at higher radii; DZ consists of 3 parts: oscillating, stationary combustible, and stationary incombustible

Conclusions

- no (or very small) viscosity in DZ $\Rightarrow$ ring instability
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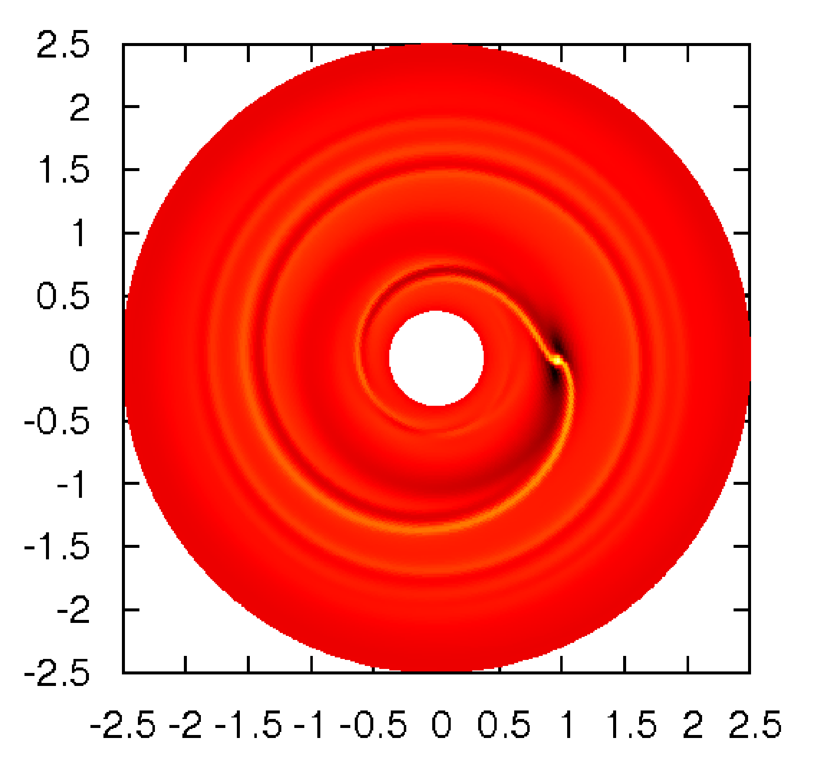
Future

- going to 3D (to see what happens with rings and mini-outbursts without the assumption of spherical symmetry)
- irradiation by the central star
- more complicated ionization structure (ionization by X-rays, . . .)

The fate of late planets

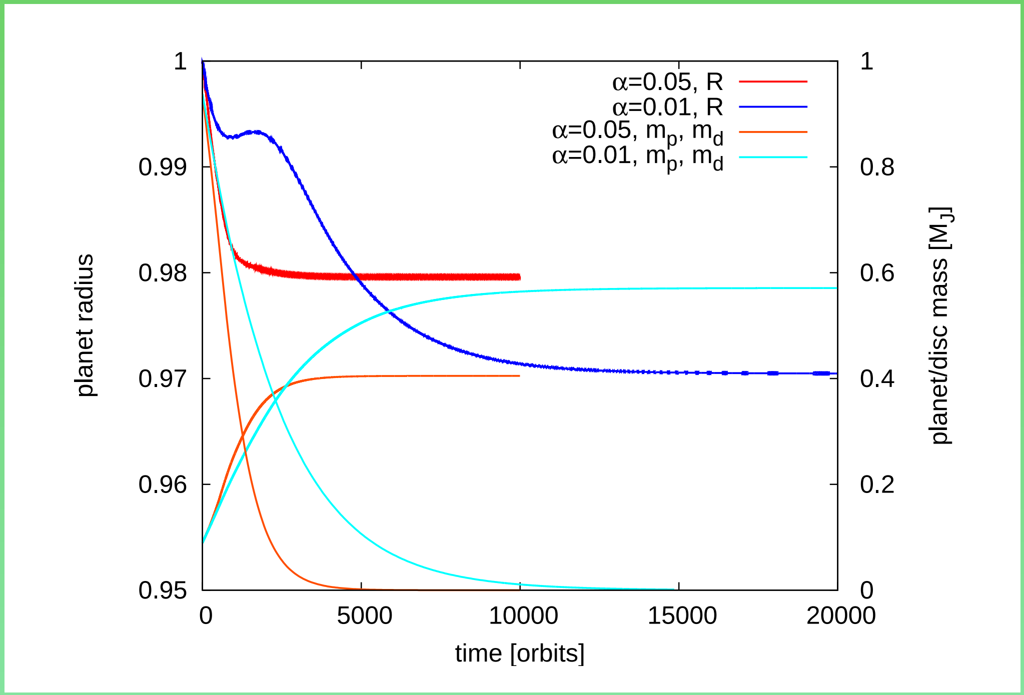
- 2d vertically averaged locally isothermal model of the disc (NIRVANA/FARGO code)
- disc is very light ($\sim 1\mathrm{M_J}$ within 12.5 AU), and viscous ($\alpha = 0.01 - 0.05$)
- planet of $\sim 30\mathrm{M}_\oplus$ - migrating, accreting mass

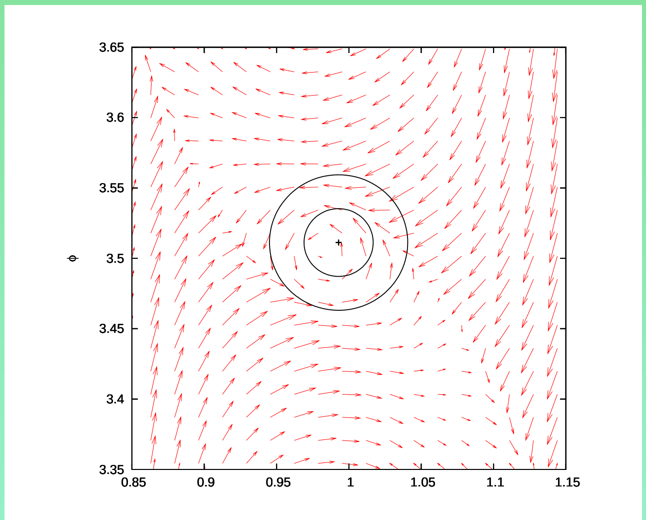


- the aim is to determine how far the planet migrates and how much mass it accretes

First results

- planet radius drops by several percent $(2 - 3)$
- planet accretes mass $0.4 - 0.6\mathrm{M_J}$





- technical problems: unphysical outwards migration occurs
- related to the poor resolution of the accretion region
- antialiasing seems to help

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