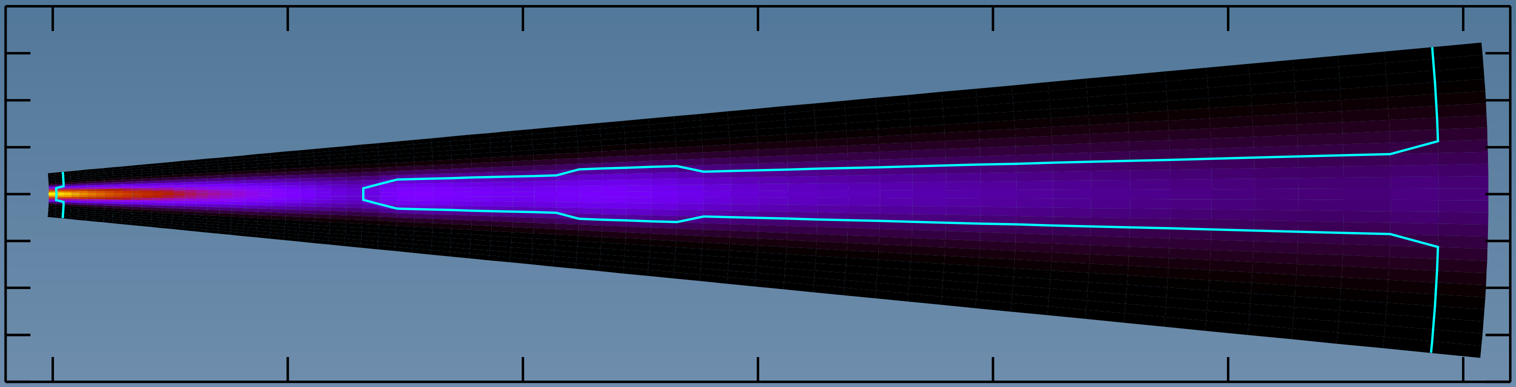
Layered accretion in protoplanetary disks

(R. Wünsch, M. Różyczka, H. Klahr)



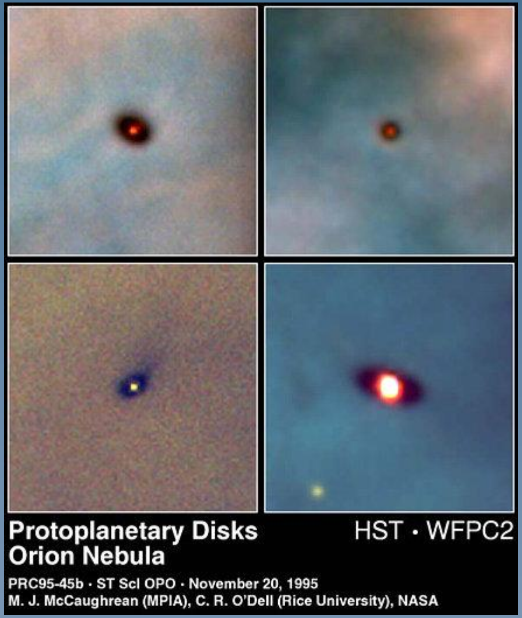
Outline:

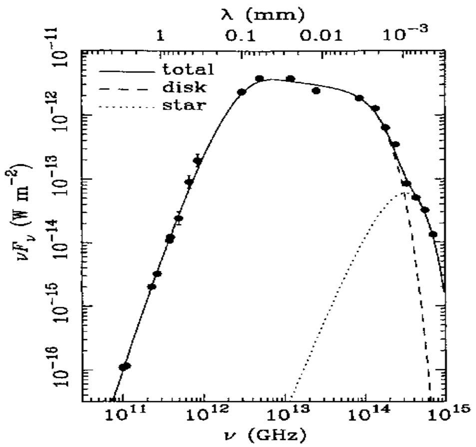
1 Protoplanetary disks
2 FU Ori outbursts
3 Layered-disk model
4 Ring instability
5 Evolution of the dead zone

Protoplanetary disks: observational evidence

Optical/NIR:

- Asymmetric profiles of forbidden emission lines (Edwards et al., 1987)
- Stellar light scattered on dust particles (Beckwith et al., 1989)
- Dark silhouettes in Orion nebulae and other HII regions


Protoplanetary Disks
Orion Nebula
HST · WFPC2
PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



(a) SED for HL Tau

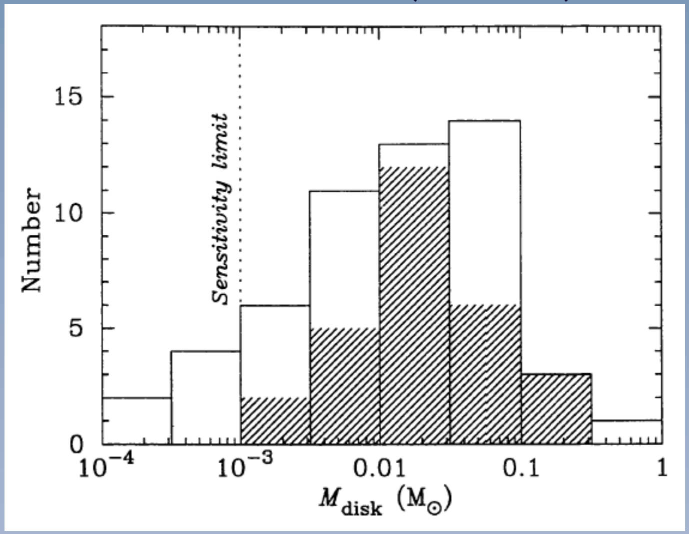
Millimeter/submillimeter interferometry:

- Broadband emission from the dust (Beckwith et al., 1990)
- CO rotational transitions suggest Keplerian rotational profile

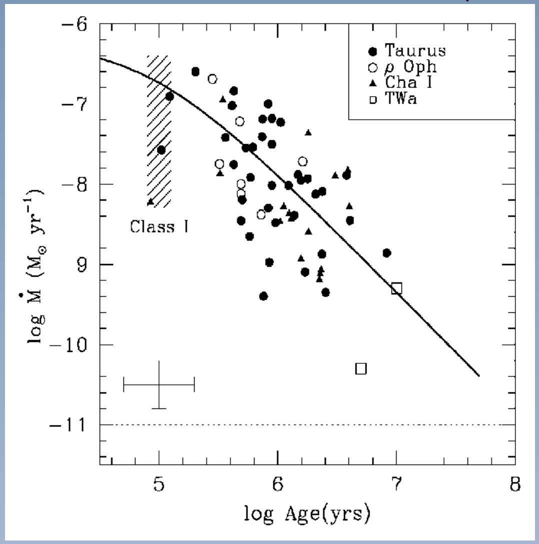
Protoplanetary disks: observed properties

- Frequency: cca 50% of TTS
- Mass: 0.01 - 0.1 $M_\odot$ (from optically thin mm emision)
- Size: 100 - 1000 AU
- Lifetime: $\sim 10^7$ yr (from ages of TTS)
- Accretion rate: 10^{-9} - 10^{-6} $M_\odot yr^{-1}$
(from optical/UV excess from inner boundary layer)

Chandler (1998)



Muzerolle et. al (2000)



Protoplanetary disks: formation and evolution

1 **Collapse of the primordial cloud: in** $\sim 10^4$ **yr**

2 **Formation stage:** $\sim 10^5$ **yr**

- disk hidden by the stellar gaseous envelope
- energetic mass outflows and jets
- fast evolution due to gravitational instabilities
- finally protostellar envelope dispersed by created pre-MS star

3 **Viscous stage:** $\sim 10^7$ **yr**

- geometrically thin accretion disk, Keplerian rotation
- evolution given by viscosity (probably due to MHD turbulence)
- planets are formed during this stage $\rightarrow$ protoplanetary disk
- finally disappears (accretion onto star, environmental effects, planet formation)

Protoplanetary disks: Standard model

- steady state model: $\dot{M} = \mathrm{const}$
- mass and angular momentum conservation:

$$\Sigma = \frac{\dot{M}}{3\pi\nu}\left[1 - \left(\frac{R_*}{r}\right)^{1/2}\right]$$

- α-viscosity: $\nu = \alpha c_s H$ `(Shakura & Sunayev, 1973)`
- energy released by accretion dissipated locally:

$$\frac{9}{8}\Sigma\nu\Omega^2 = \sigma T_e^4$$

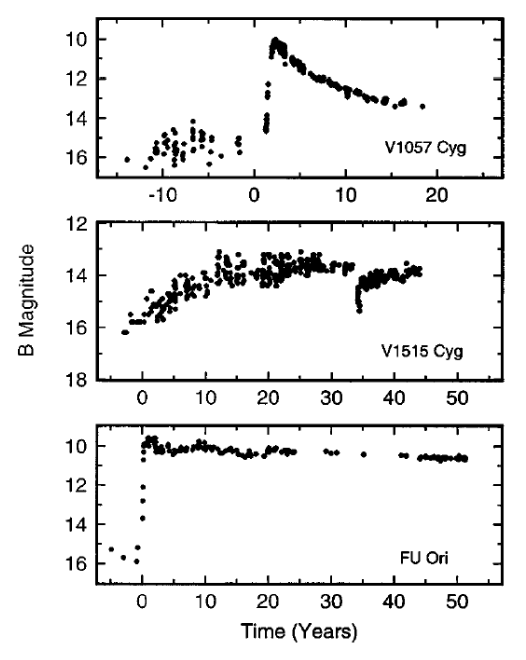
- emission is optically thick: $T_c^4 = \frac{3}{16}\Sigma\kappa T_e^4$ `(Hubeny, 1990)`
- disk is geometrically thin: $\Omega = \left(\frac{GM}{R}\right)^{1/2}$
- vertical hydrostatic equilibrium: $H = \frac{c_s}{\Omega}$

Solution:

Radial profiles of all interesting quantities (Σ, T_e, T_c, H, . . .) are power-laws with exponents dependent on the opacity $\kappa = \kappa(\rho, T)$. $\dot{M}$ and α are the free parameters.

FU Ori outbursts

- young stars, large increases in optical brightness $\sim$ 4 mag
- decay timescales: 10-100 yr
- reflection nebulae, heavily extincted, large IR excess from circumstellar dust
- AD models: $\dot{M}$ increases from 10^{-7} to 10^{-4} $M_\odot$ yr^{-1}, $\sim$0.01 $M_\odot$ accreted during one outburst



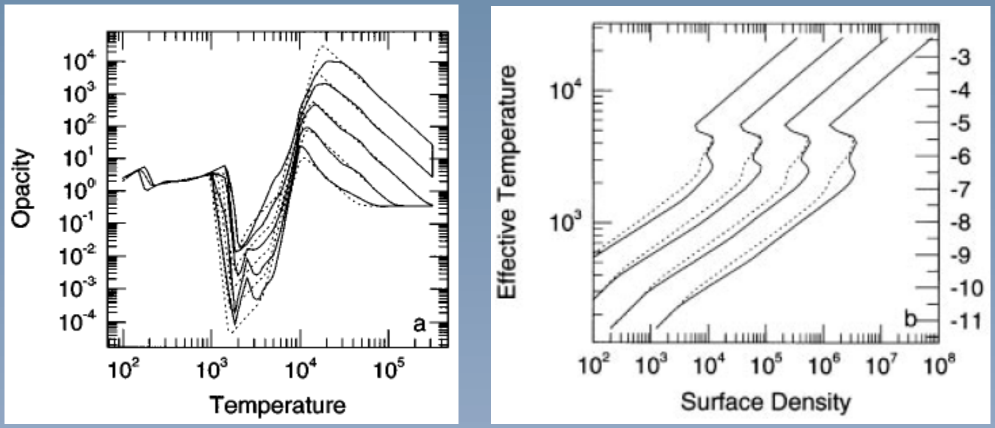
FU Ori objects (Hartmann & Kenyon, 1996)

Object	Outburst	t(Rise)	t(Decay)	d(kpc)	$L/L_\odot$	CO flow	Jet/HH
FU Ori	1937	$\sim$ 1 yr	$\sim$ 100 yr	0.5	500	no	no
V1057 Cyg	1970	$\sim$ 1 yr	$\sim$ 10 yr	0.6	800-250	yes	no
V1515 Cyg	1950s	$\sim$ 20 yr	$\sim$ 30 yr	1.0	200	no	no
V1735 Cyg	$\sim$ 1957-65	$<$ 8 yr	$>$ 20 yr	0.9	$>$ 75	yes	no
V346 Nor	$\geq$ 1984	$<$ 5 yr	$>$ 5 yr	0.7	?	yes	yes
BBW 76	$<$ 1930	?	$\sim$ 40 yr	1.7?	?	?	no
Z CMa	?	?	$>$ 100 yr	1.1	600	yes	yes
L1551 IRS5	?	?	?	0.15	$\geq$ 20	yes	yes
RNO 1B,C	?	?	?	0.8	?	yes?	no

FU Ori outbursts: models

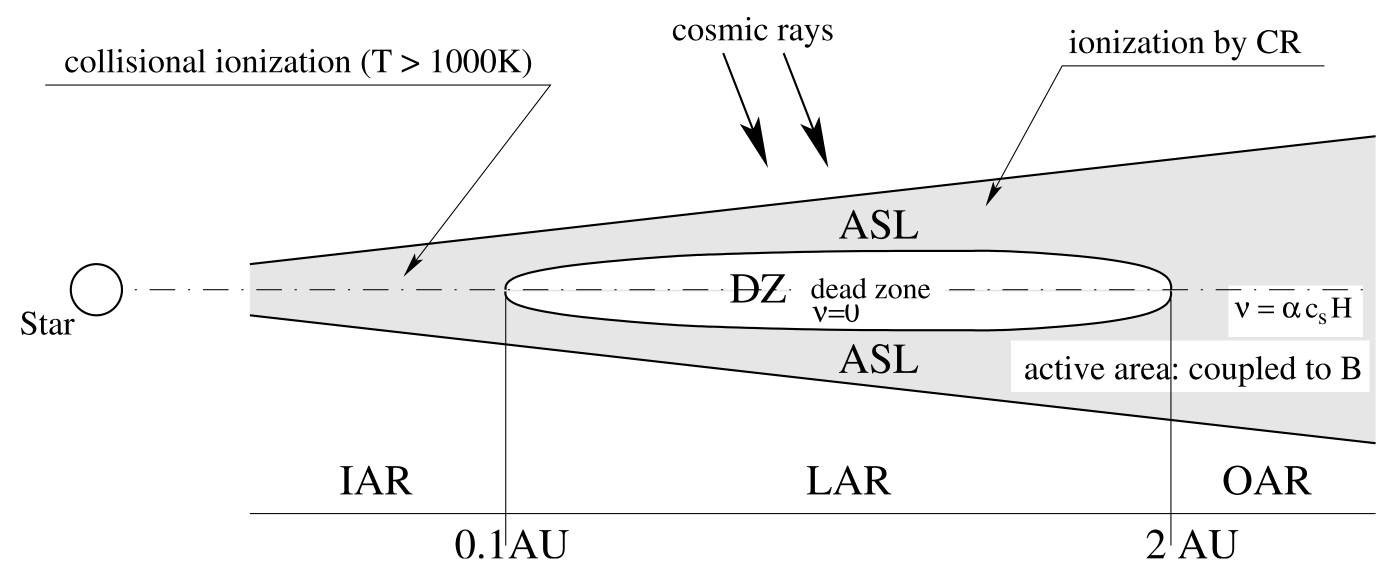
Models have to explain rise times $\sim$1 yr
$\Rightarrow$ eruption must involve inner region ($<$1AU) of the disk.

- Triggering of outburst `(Bonnel & Bastien, 1992)`
  - *disk perturbed by the close passage of the companion star*
  - *but no apparent v_r shifts were observed in the brightest FU Ori objects*
- The thermal instability mechanism
  - $F_{\mathrm{vis}}/F_{\mathrm{rad}} \sim \kappa(\rho,T)T^{-3}\Sigma^2\alpha$
  - *if κ increases faster than T^3 $\Rightarrow$ instability*
  - *decay timescales too short*



- The layered-disk model
  - *accretion of material accumulated in "dead zone"*

Layered-disk: basic idea (Gammie, 1996)



- angular momentum transfer - MRI (Balbus & Hawley, 1991)
- parts of the disk are not ionized enough to be well coupled to the magnetic field
- inner active region (IAR) - collisional ionization
- layered accretion region (LAR) - surface active layers (ASL) ionized by cosmic rays shield the dead zone (DZ) near the mid-plane
- outer active region (OAR) - low surface density, CR are able to ionize whole disk

Layered-disk: physical processes

- MRI occurs for: $Re_M \equiv \frac{V_A H}{\eta} > 1$
- Alfven velocity related to α-viscosity: $V_A = \alpha^{1/2} c_s$
- resistivity η related to the ionization degree $x = n_e/n_H$:

$$\eta = 6.5 \times 10^3 x^{-1} \mathrm{cm}^2 \mathrm{s}^{-1}$$

- using $H = c_s/\Omega$ magnetic Reynolds number:

$$Re_M = 7.4 \times 10^{13} x \alpha^{1/2} \left(\frac{R}{AU}\right)^{3/2} \left(\frac{T}{500K}\right) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

- collisional ionization: $x = x(\rho, T)$ `(Umebayashi, 1983)`

$$x \sim \log(\rho), \qquad x(T) = \begin{cases} 10^{-16} & \text{for} \quad T \leq 800\ \ K \\ 10^{-13} & \text{for} \quad T \sim 900\ \ K \\ 10^{-11} & \text{for} \quad T \geq 1000\ \ K \end{cases}$$

- CR ionization: stopping depth $\Sigma_0 \sim 100\ \ \mathrm{g/cm}^2$

`(Umebayashi & Nakano, 1981)`

$$x = \left(\frac{\zeta}{\beta n_H}\right)^{1/2} = 1.6 \times 10^{-12} \left(\frac{T}{500\mathrm{K}}\right)^{1/4} \left(\frac{\zeta}{10^{-17}\mathrm{s}^{-1}}\right)^{1/2} \left(\frac{n_H}{10^{13}\mathrm{cm}^{-3}}\right)^{-1/2}$$

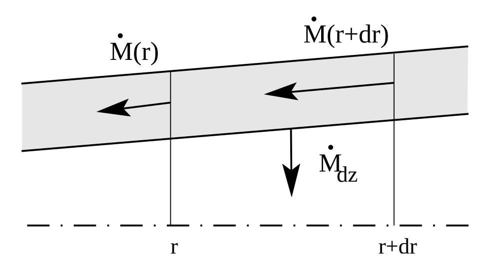
Layered disk: analytical solution

- Basic equations for one surface active layer:

$$\dot{M} = 6\pi r^{1/2}\frac{\partial}{\partial r}(2\Sigma_a \nu r^{1/2}), \qquad \frac{9}{4}\Sigma_a \nu \Omega^2 = \sigma T_e^4, \qquad \nu = \alpha c_s H$$

$$T_c^4 = \frac{3}{8}\Sigma_a \kappa(\rho, T_c) T_e^4, \qquad \Omega = \left(\frac{GM}{R}\right)^{1/2}, \qquad H = \frac{c_s}{\Omega}$$

- $\rho_c, T_c, T_e, \dot{M}, H, \ \ldots$ - power-laws
- $\Sigma_a = \mathrm{const} \ \Rightarrow \ \dot{M} = \dot{M}(r)$ increasing with r
- accumulation of mass in DZ:
  $\dot{\Sigma}_{\mathrm{DZ}} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$
- accretion cannot be steady - when Σ_{DZ} is high enough, DZ mass is accreted in an outburst like event $\Rightarrow$ FU Orionis



Numerical model

- RHD code TRAMP: `(Klahr et al., 1999)`

  (Three-dimensional RAdiation-hydrodynamical Modeling Project)

- solves set of Navier-Stokes equations:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

$$\frac{\partial\rho\mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\rho\mathbf{v} = -\nabla P - \rho\nabla\Phi + \nabla\cdot\mathbf{T} \qquad P = \frac{kT}{\mu m_H}\rho$$

$$c_v\rho\left[\frac{\partial T}{\partial t} + (\mathbf{v}\cdot\nabla)T\right] = -P\nabla\cdot\mathbf{v} + \mathbf{T}:(\nabla\mathbf{v})$$

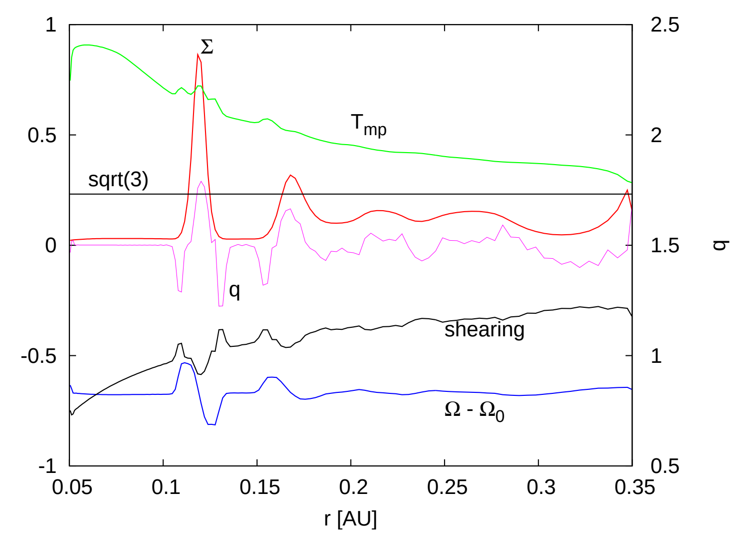
- at the end of time-step: radiation transfer

$$\frac{\partial E_r}{\partial t} = -\nabla\cdot\mathbf{F}\ , \quad \text{where} \quad E_r = aT^4\ , \quad \mathbf{F} = -\frac{\lambda c}{\rho\kappa}\nabla E_r$$

- 2D axially symmetric in spherical (r,θ) coords.
- initial conditions: analytical model (vertically isothermal)
- viscosity:
  - ▷ $\alpha = 0.01$ - *surface layers* ($\Sigma_a = 100\,\mathrm{g\,cm^{-2}}$) *and inner region* ($T > 1000\mathrm{K}$)
  - ▷ $\alpha = 0$ - *elsewhere (dead zone)*

Ring instability

- dead zone decomposes into rings
- ring instability mechanism:
  - ▷ *ring-like perturbation changes* Ω
  - ▷ *less shearing at the inner edge of the ring*
  - ▷ *it increases the difference between the amount of mass flowing to the ring from outwards and amount flowing from the ring inwards*
  - ▷ *positive feedback* → *growing of the ring*



- rings may work as traps for the dust
  → formation of planets
- rings may decay due to the hydrodynamic instability, if $q > \sqrt{3}$ $(\Omega \sim r^{-q})$ `(Papaloizou & Pringle, 1985)`

Ring instability - analytical description

- thickness of the dead zone important for $\dot{M}$ `(Huré, 2002)` (vertical gravity determines active layer structure)
- dimensionless disk thickness: $\delta = \frac{H_a + H_{\mathrm{DZ}}}{H_a}$
- rotational velocity corrected to mid-plane pressure:

$$\Omega^2 = \Omega_0^2 + \frac{1}{\rho_m}\frac{\partial P_m}{\partial r}$$

- ring-like perturbation of δ:

$$\delta = \delta_0 + \delta_k \cos(kR), \text{ where } R = r - r_0$$

δ_0 - unperturbed disk thickness, r_0 - position of the ring,

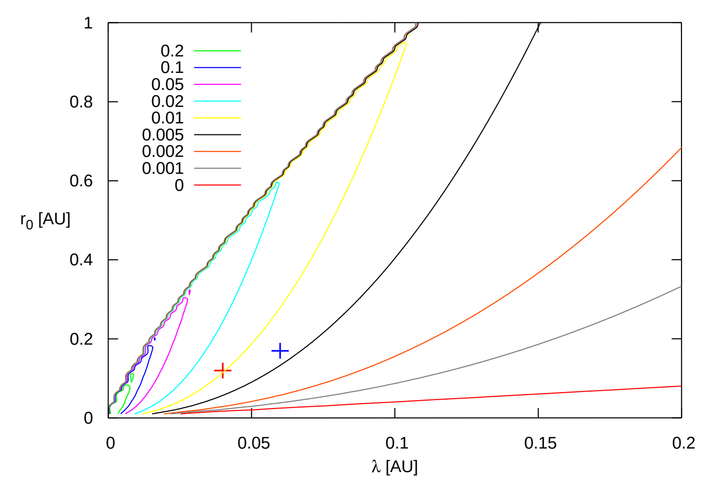
k - wavenumber

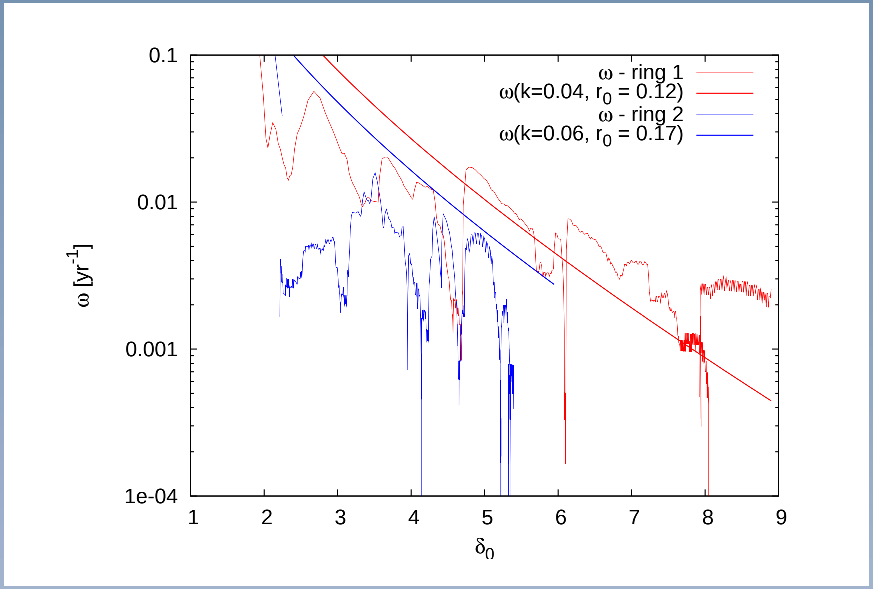
- inserting into equations of layered disk, linearization
- → perturbation growth given by the equation:

$$\dot{\delta}_k = \omega(r_0, \delta_0, k)\delta_k$$

Ring instability - dispersion relation

- ω diverges for $k \to \infty$ ($\lambda \to 0$) - radial extent of the ring given just by thermal motion of particles
- rings in numerical model several times larger than expected





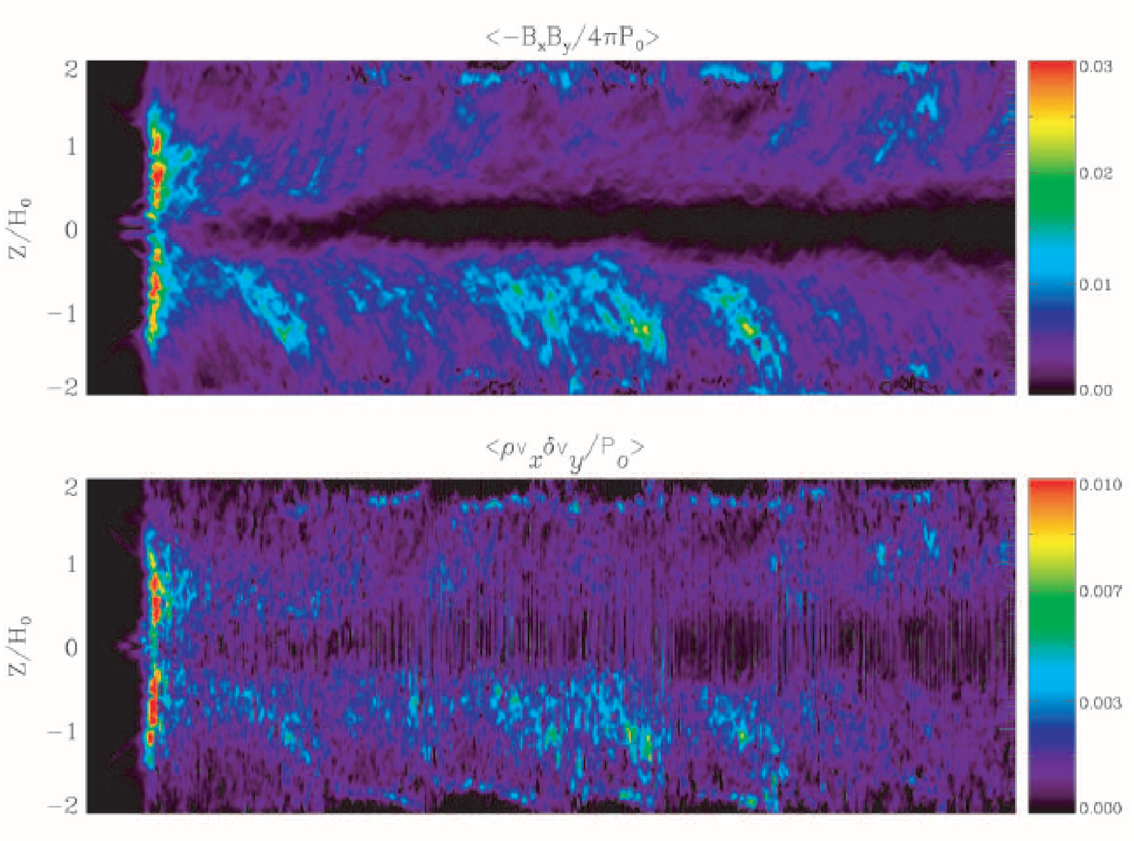
- growth rate of rings and the trend of dependence on δ_0 roughly in agreement with analytical model

Layered-disks: MRI simulations

`(Fleming & Stone, 2003)`

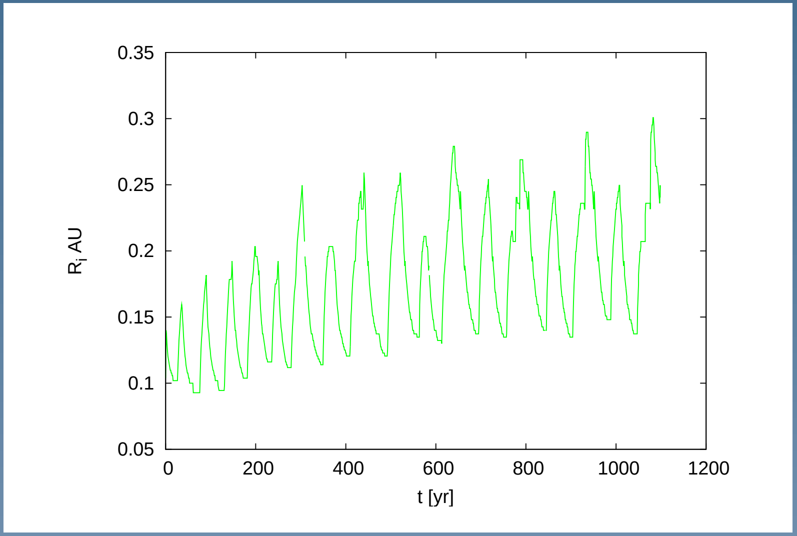
- indications for a small viscosity in the dead zone
- non-ideal MHD ($\eta \neq 0$), shearing box, isothermal EOS

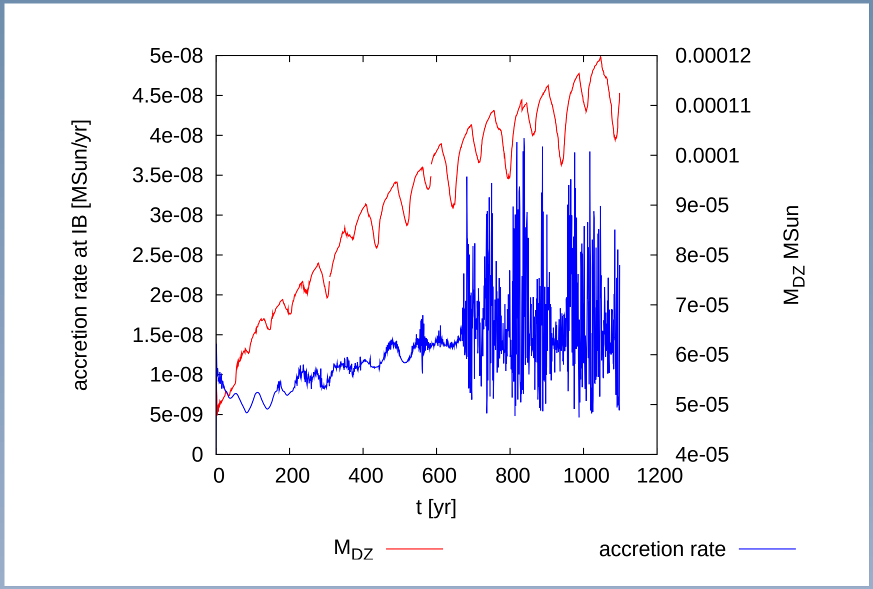
- Maxwell stress vanishes in DZ - MHD turbulence decays
- Reynolds stress non-zero in DZ - HD turbulence survives due to perturbations from active layers (10% of Maxwell s.)



Evolution of the dead zone

- inner edge of DZ oscillates
- timescale $\sim 10 - 100\mathrm{yr}$
- DZ continuously depleted from inner edge





- small changes in $\dot{M}$ (amplitude $0.5 - 1 \times 10^{-8}\ \mathrm{M}_\odot \mathrm{yr}^{-1}$)
- mass stored in the dead zone grows

Conclusions

- the dead zone with zero viscosity is a subject of the ring instability
- in the case of small viscosity in DZ the oscillations of the inner edge occur
- mass is continuously removed from the inner part of the dead zone - it cannot serve as a mass reservoir for the FU Ori type outburst

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