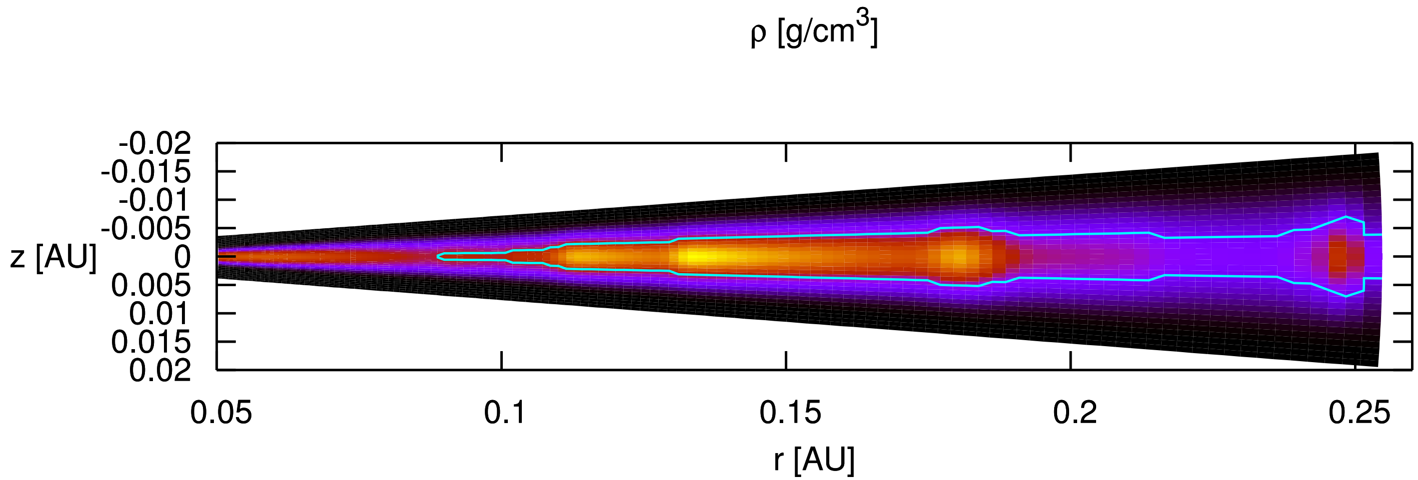
Layered accretion in protoplanetary disks



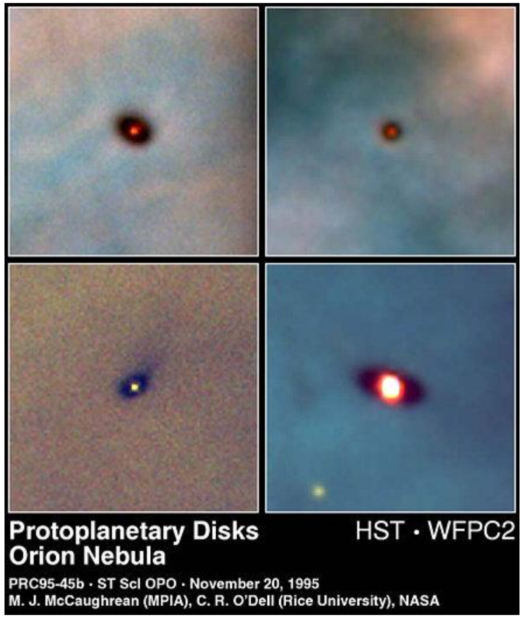
Outline:

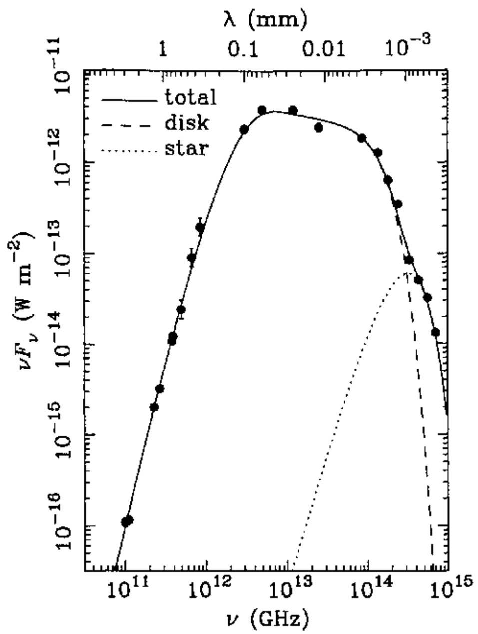
1. **Protoplanetary disks**
2. **FU Ori outbursts**
3. **Layered-disk model**
4. **Simulations of LD using TRAMP**

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





(a) SED for HL Tau

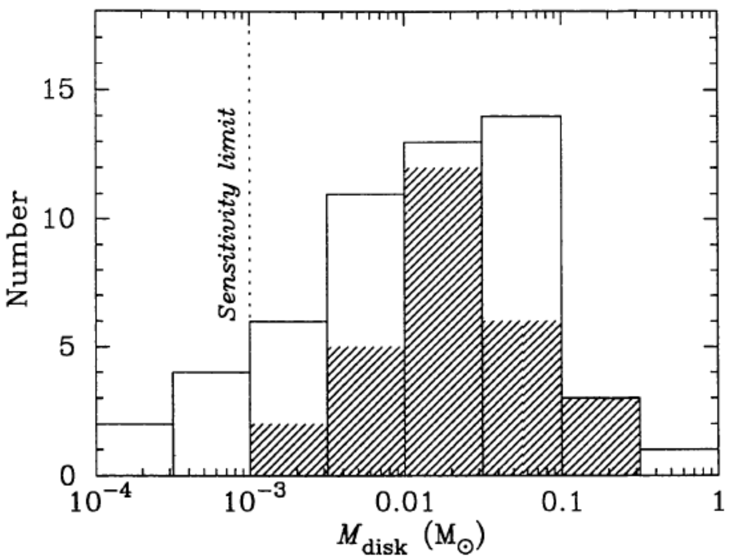
Millimeter/submillimeter interferometry:

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

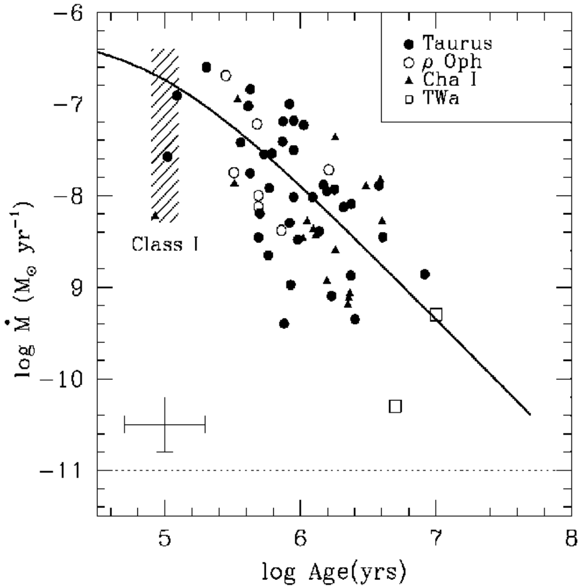
Protoplanetary disks: observed properties

- **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

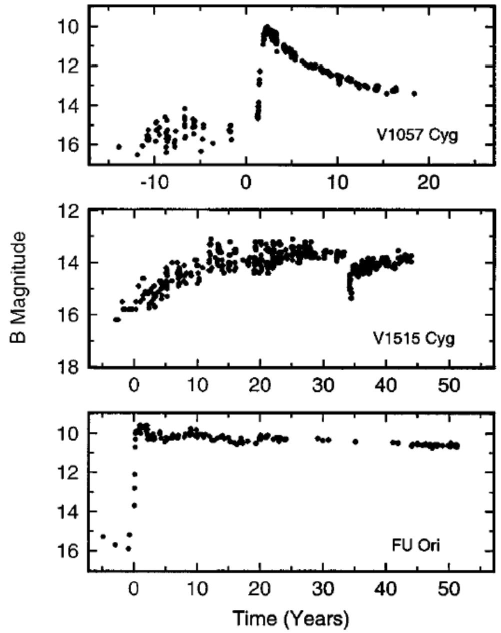
- **steady state model:** $\dot{M} = \mathrm{const}$
- **mass and angular momentum conservation:** $\Sigma = \frac{\dot{M}}{3\pi\nu}\left[1 - \left(\frac{R_*}{r}\right)^{1/2}\right]$
- **α-viscosity:** $\nu = \alpha c_s H$ **(Shakura & Sunayev, 1973)**
- **energy released by accretion dissipated locally:** $\frac{9}{8}\Sigma\nu\Omega^2 = \sigma T_e^4$
- **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 indexes 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**



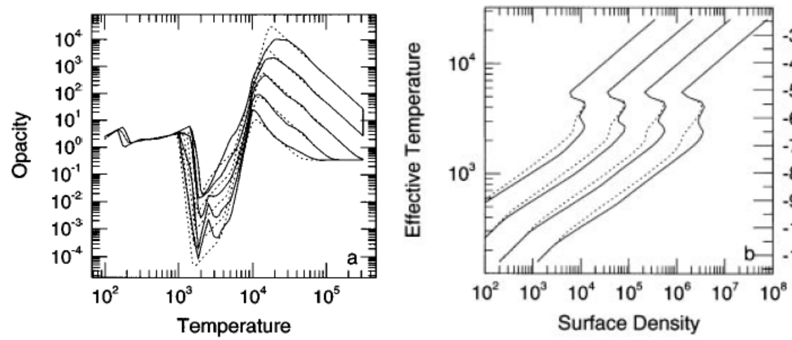
FU Ori objects (Hartmann & Kenyon, 1996)

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

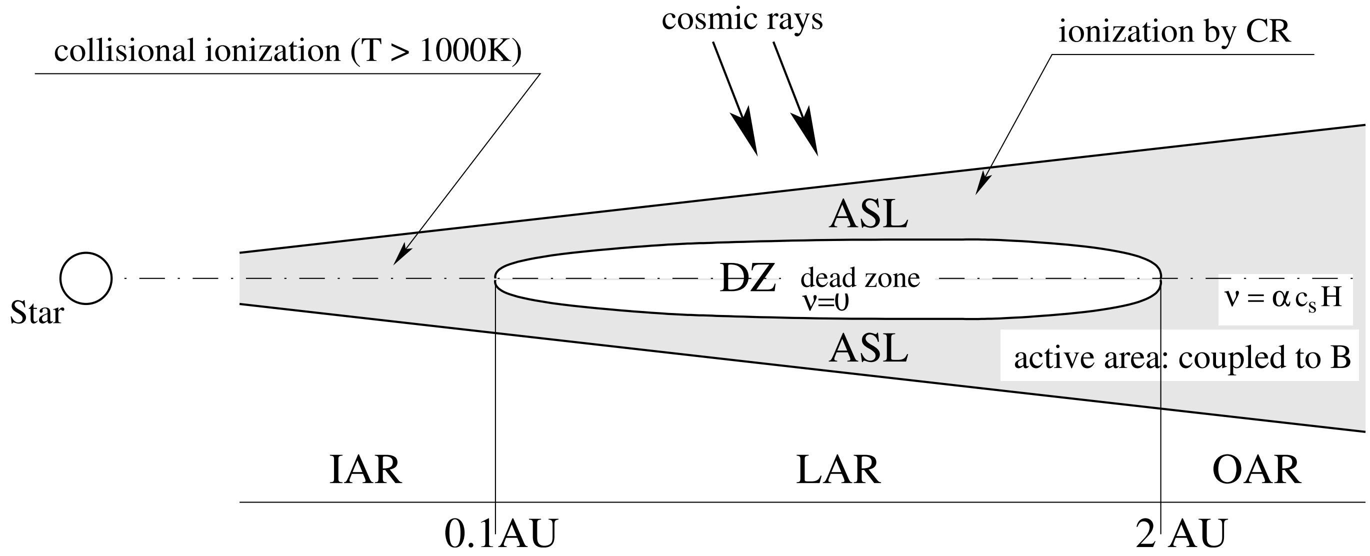
Models have to explain rise times $\sim$1 yr $\Rightarrow$ eruption must involve inner region (<1AU) of the disk.

- **Triggering of outburst** (Bonnel & Bastien, 1992)
  - **disk perturbed by the passage of close companion star**
  - **but no apparent v_r shifts were observed in the brightest FU Ori objets**
- **The thermal instability mechanism**
  - $F_{\rm vis}/F_{\rm rad} \sim \kappa(\rho, T) T^{-3} \Sigma^2 \alpha$
  - **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)**

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

- **CR ionization: stopping depth** $\Sigma_0 \sim 100\ \mathrm{g/cm}^2$ **(Umebayashi & Nakano, 1981)**

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

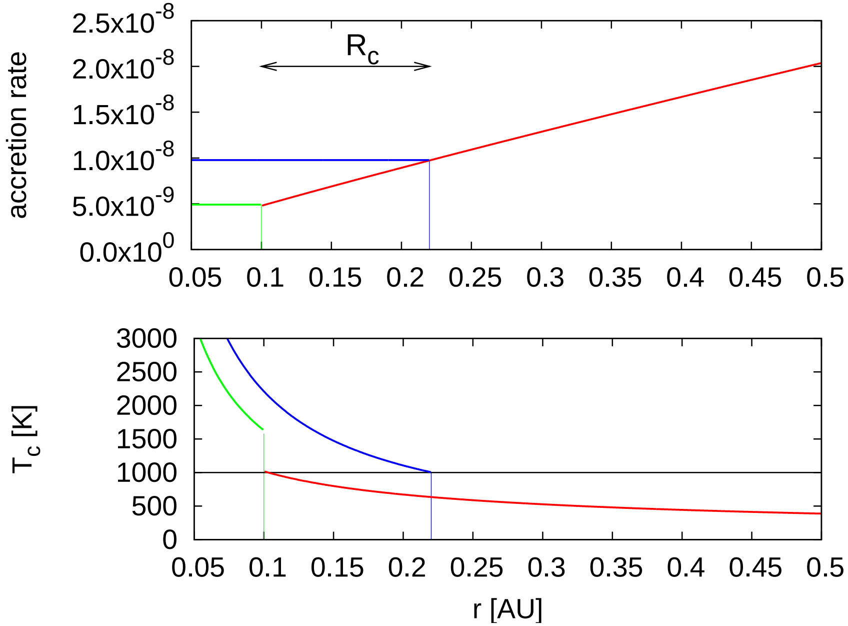
Layered disk: analytical solution

- **Basic equations for one surface active layer:**

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

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

- $\rho_c, T_c, T_e, \dot{M}, H,$ **. . . – power-laws**



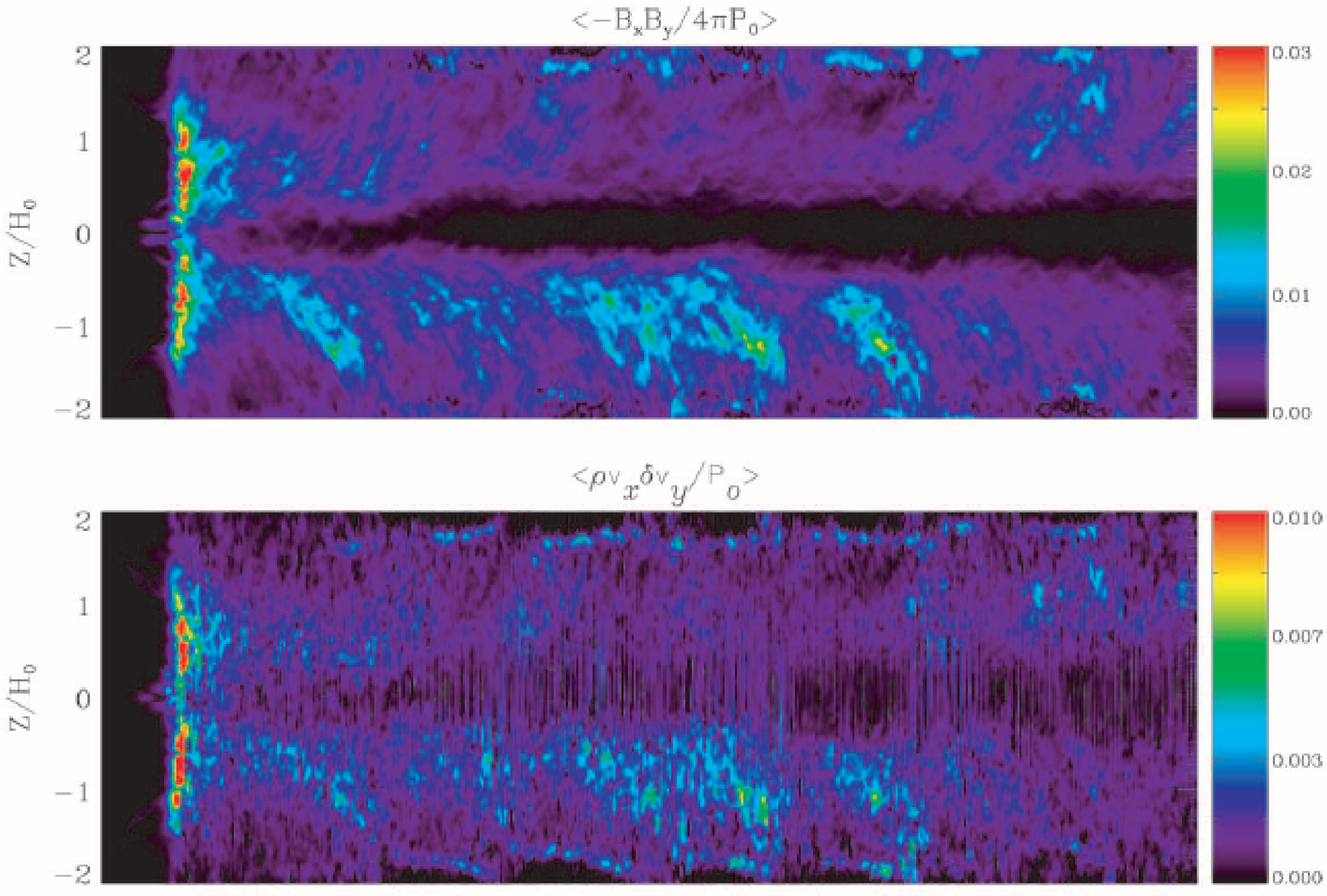
- $\Sigma_a = \text{const} \;\Rightarrow\; \dot{M} = \dot{M}(r)$ **increasing with** $r \Rightarrow$ **mass accumulates in DZ**

- **inner boundary of LAR at** R_c**, given by** $T_c > 1000\text{K}$ **(in LAR or IAR?) – depends on radial radiation transfer**

- $\dot{M}$ **in IAR depends on** R_c

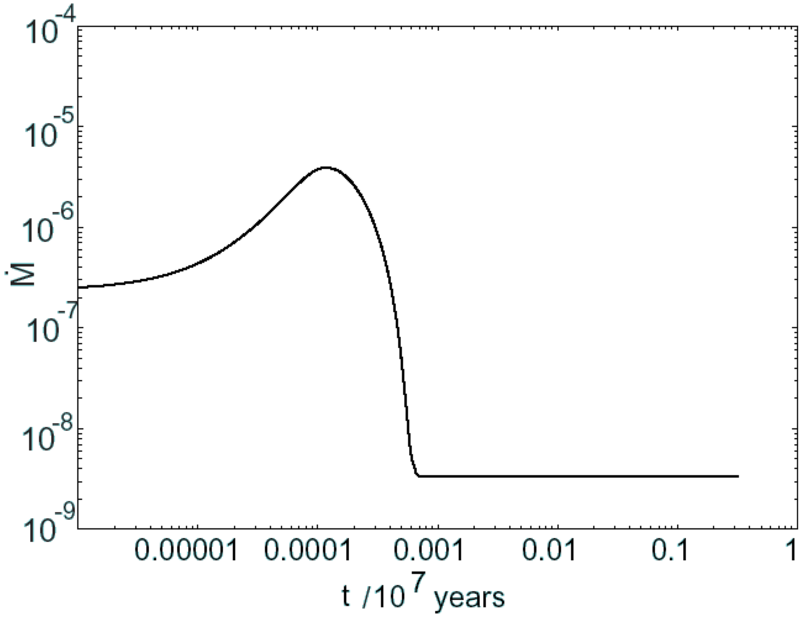
Layered-disks: MRI simulations (Fleming & Stone, 2003)

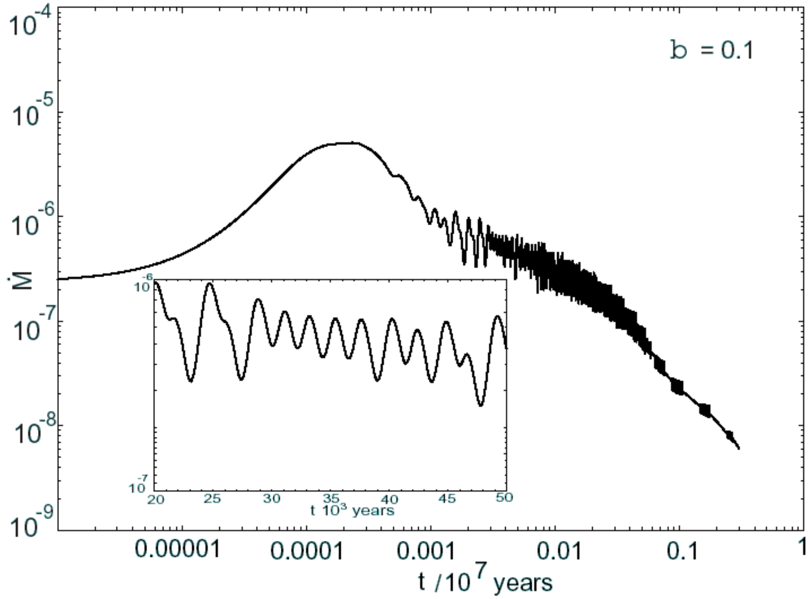
- non-ideal MHD ($\eta \neq 0$), shearing box, isothermal EOS
- Maxwell stress vanishes in DZ – MHD turbulence decays
- Reynolds stress non-zero in DZ – HD turbulence survives due to perturbations from active layers (10% of Maxwell s.)



Layered-disks: long-term evolution

- LD model predicts $\dot{M}$ independent on time
- but observations of PPD indicate decrease of $\dot{M}$
- possible solutions:
  - decrease of opacity due to grain growth
  - changing stellar radiation
  - small viscosity in DZ: $b = \alpha_{DZ}/\alpha_{AR}$ (Stepinski, 1999)





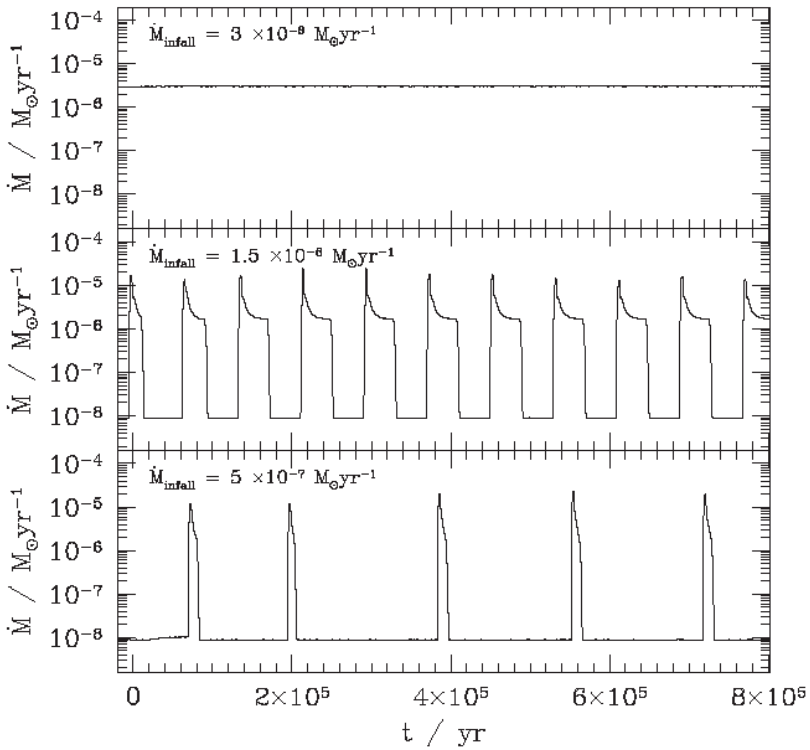
Layered-disks: gravitational instability of DZ

(Armitage et al., 2001)

- **mass accumulates in DZ until it becomes gravitationally unstable and viscous**
- **gravitational instability for** $Q < Q_{\rm crit} \equiv 2$**,** $Q = \frac{c_S \Omega}{\pi G \Sigma}$
- $\alpha_{\rm grav} = 0.01 \left(\frac{Q_{\rm crit}^2}{Q^2} - 1 \right)$ **for** $Q < Q_{\rm crit}$ **(Lin & Pringle, 1987)**
- **numerically solve equation**

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} \left(\nu \Sigma_a r^{1/2} \right) \right] + \dot{\Sigma}(r,t)$$

- $\dot{\Sigma}(r,t)$ **– infall of mass to the outer region**
- **steady solution for very high mass infall**
- **otherwise outbursts:** $t_{\rm outburst} = 10^4 {\rm yr}, t_{\rm recur} = 10^5 {\rm yr}$



LD: HD simulations with radiative transfer

(R. Wünsch, M. Różyczka & H. Klahr)

Aim:

- **explore the influence of radiation transfer on the layered disk model**
- **how the DZ changes, does it survive at all?**

HD code TRAMP: (Hubert Klahr)

Three-dimensional RAdiation-hydrodynamical Modeling Project

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

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla p}{\rho} - \nabla \Phi + \nabla \cdot \mathbf{W}$$

$$c_v \rho \left[\frac{\partial T}{\partial t} + (\mathbf{v} \cdot \nabla) T \right] = -p \nabla \cdot \mathbf{v} + \frac{Tr(\mathbf{W^2})}{2\rho\nu} - \nabla \cdot \mathbf{F}$$

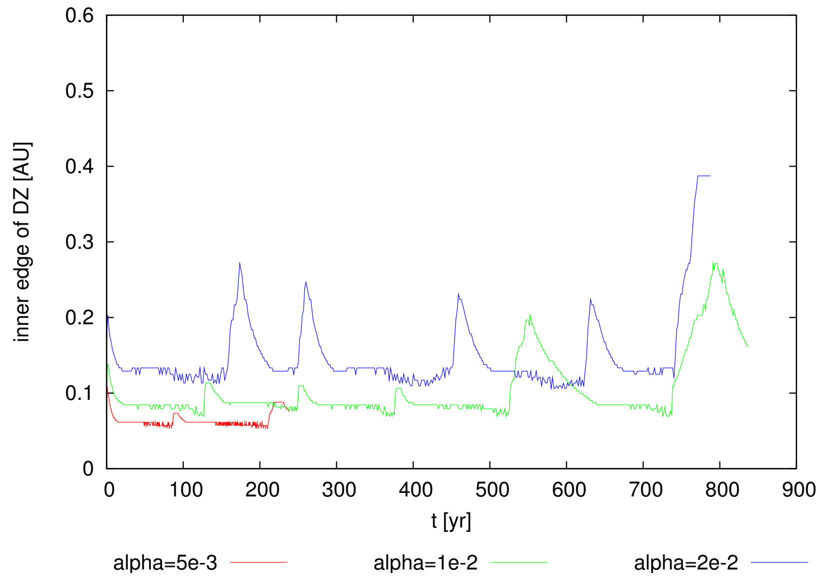
$$p = \frac{kT}{\mu m_H} \rho$$

$$\mathbf{F} = -\frac{\lambda c}{\rho \kappa} \nabla E_r$$

LD simulations using TRAMP

- 2D axially symmetric in spherical (r, θ) coords.
- initial conditions: analytical model
- surface layers ($\Sigma_a = 100\mathrm{g\,cm}^{-2}$) and inner region ($T > 1000\mathrm{K}$) $\alpha = 0.005 - 0.02$, for other parts (DZ) $\alpha = 0$
- accumulation of mass in DZ
- inner edge of DZ is heated by the adjacent active disk
- increasing optical depth leads to the increase of T
- when T reaches 1000K, inner part of DZ is ignited

- oscillations of the inner edge of DZ – minioutbursts, timescale $\sim 100\mathrm{yr}$
- $\dot{M}$ increases only several times
- may prevent DZ to accumulate enough mass for FU Ori type outburst



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