Layered accretion in protoplanetary disks

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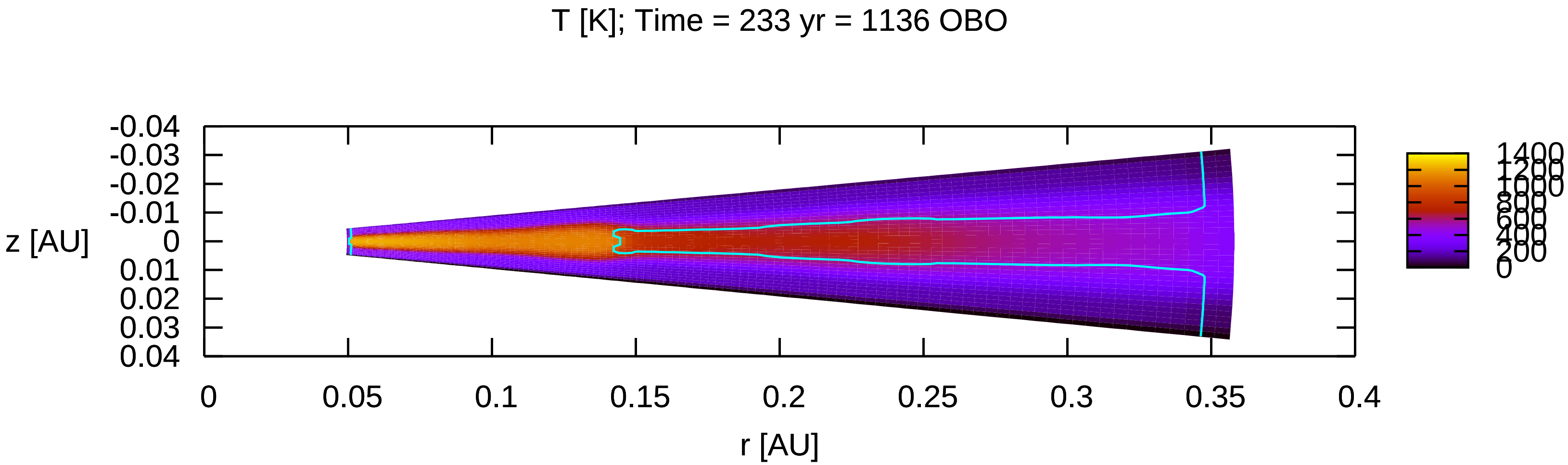
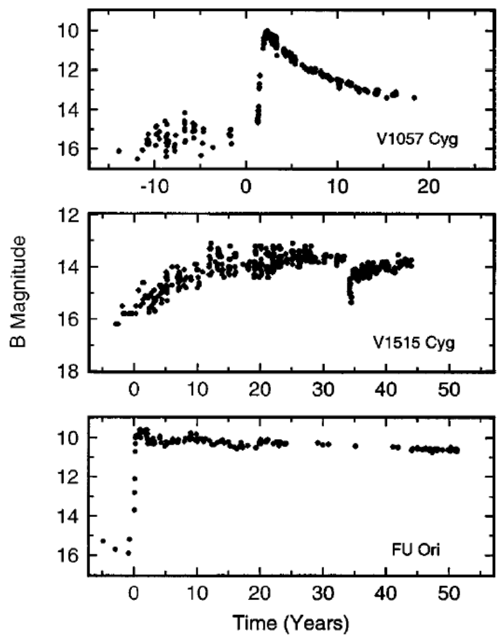


Outline:

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

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)

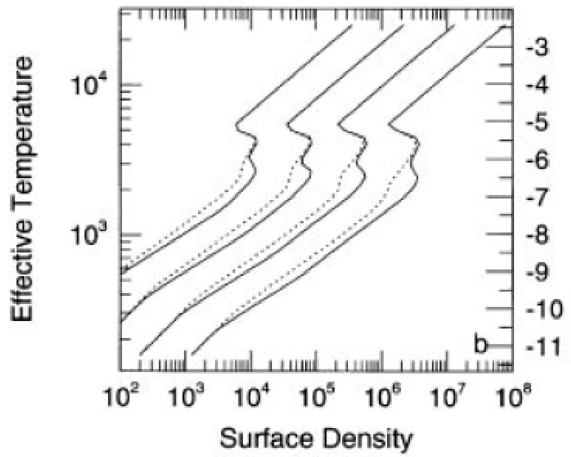
Object	Outburst	t(Rise)	t(Decay)	d(kpc)	$L/L_\odot$	CO flow	Jet/HH
FU Ori	1937	$\sim$ 1 yr	$\sim$ 100 yr	0.5	500	no	no
V1057 Cyg	1970	$\sim$ 1 yr	$\sim$ 10 yr	0.6	800-250	yes	no
V1515 Cyg	1950s	$\sim$ 20 yr	$\sim$ 30 yr	1.0	200	no	no
V1735 Cyg	$\sim$ 1957-65	$<$ 8 yr	$>$ 20 yr	0.9	$>$ 75	yes	no
V346 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 ~1 yr ⇒ 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 objects
- **The thermal instability mechanism**
  - S-curve: balance between viscous heating and rad. cooling
  - predicts increase of accretion rate consistent with observations
  - decay timescales too short

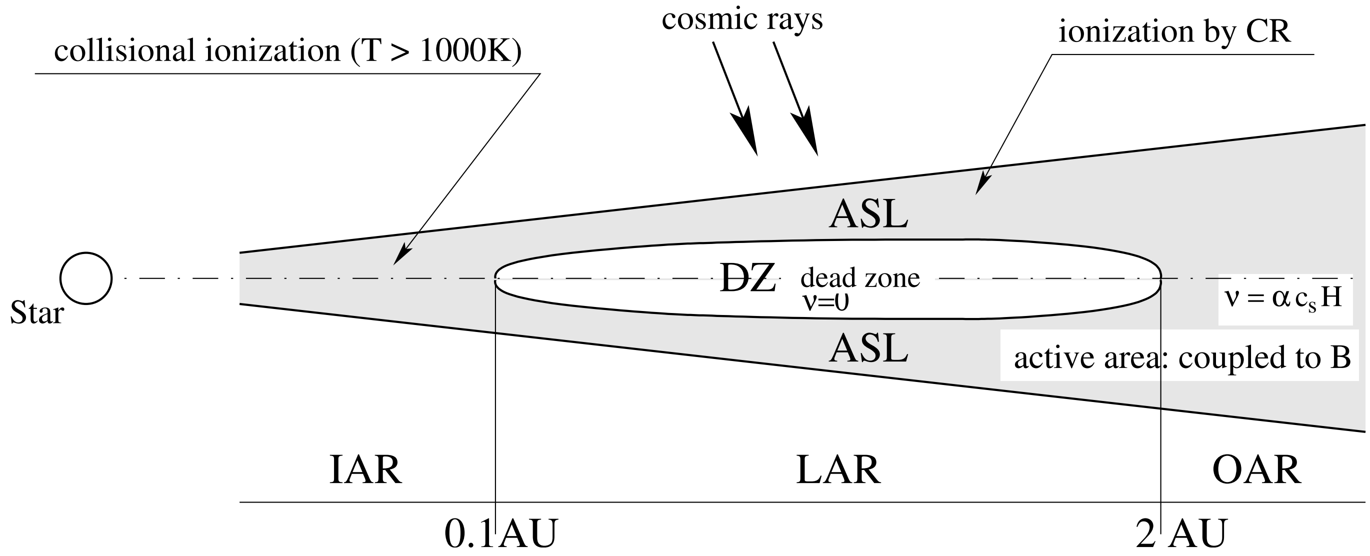
Hartmann & Kenyon (1996)



$\alpha = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$

- **The layered-disk model**
  - accretion of material accumulated in "dead zone"
  - can DZ with such amount of mass ($0.01\ M_\odot$) survive?

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) – active surface layers (ASL) ionized by cosmic rays shields 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 the layered accretion region:**

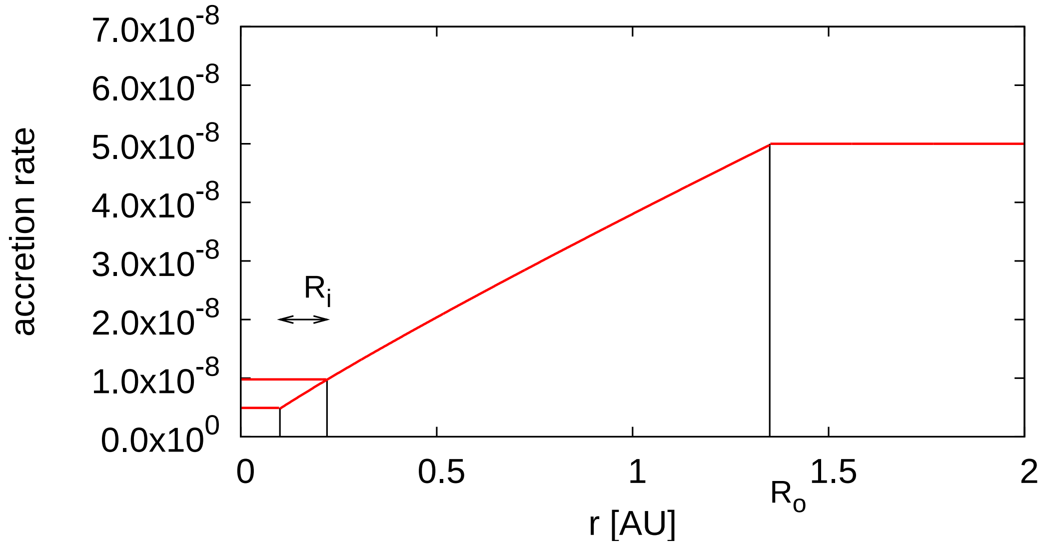
$$\dot{M} = 6\pi r^{1/2} \frac{\partial}{\partial r}(2\Sigma_a \nu r^{1/2}), \qquad \frac{9}{4}\Sigma_a \nu \Omega^2 = \sigma T_e^4, \qquad \nu = \alpha c_s H$$

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

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

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

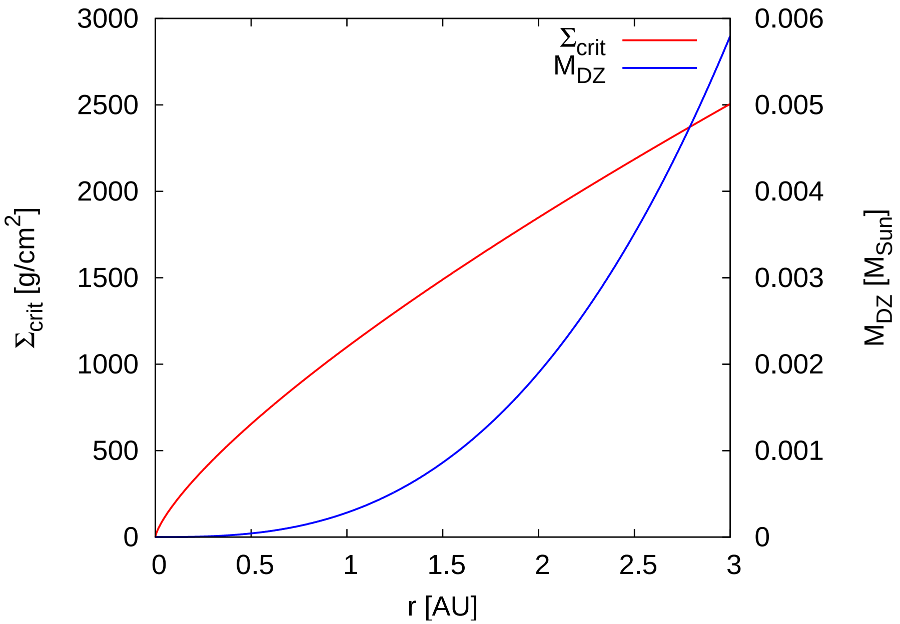
- **temperature discontinuity at inner boundary of DZ** R_i $\Rightarrow$ **radiation transfer may shift** R_i **outwards (and increase** $\dot{M}$**)**



Layered disk: mass accumulated in DZ

- **mass accumulated in DZ can be made active if** $\Sigma = \Sigma_{\rm crit}$
- $\Sigma_{\rm crit}(r)$ – **surface density of the standard** α**-disk with** $T = 1000\ K$ **at radius** r
- **estimate the total mass in DZ:**

$$M_{\rm DZ} = \int_0^r 2\pi r' \Sigma_{\rm crit} dr'$$



Viscosity in the dead zone

- **MHD simulations of MRI show that the pure hydrodynamic turbulence in DZ may be supported by perturbations from active layers (Fleming & Stone, 2003)**
- **viscosity in DZ can explain observed decrease of accretion rate on the evolutionary time-scale (Stepinski, 1999)**

The TRAMP code (H. Klahr)

Three-dimensional RAdiation-hydrodynamical Modeling Project

- **finite-difference hydrodynamic code similar to ZEUS**
- **includes full tensor viscosity**
- **radiation transfer using flux limited diffusion approximation**

Solves the set of Navier-Stokes equations:

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

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

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

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

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

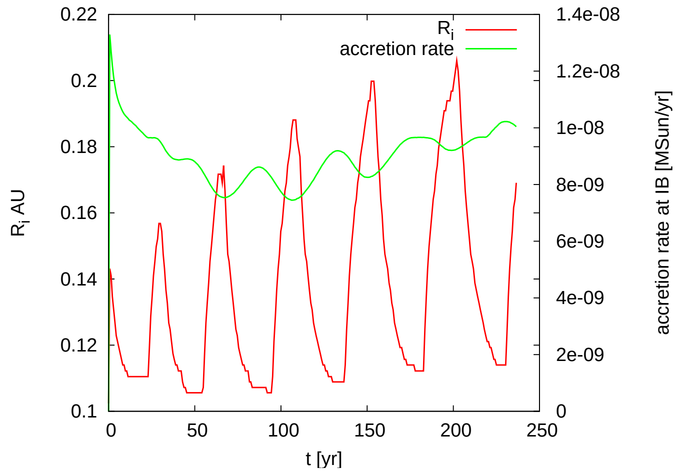
The numerical model

- **2D, axially symmetric in (r, θ)**
- **2 model types:**
  1. **Inner disk: IAR, part of LAR**
  2. **Contain whole DZ: IAR, LAR, OAR**
- **parameters:**
  $\alpha = 0.005, 0.01, 0.02$
  $b = \alpha_{\rm DZ}/\alpha = 0, 0.01, 0.1$
  $\dot{M}_{\rm OAR} = 2 \times 10^{-8} - 10^{-7}\ M_\odot\, yr^{-1}$ **(type 2 models only)**
- **initial conditions:**
  radial profiles of Σ, T, Ω according to analytical model
  $v_r = v_\theta = 0$
  vertical structure – isothermal
- **boundary conditions:**
  inner boundary: outflow
  outer boundary: inflow, $\dot{M}_{\rm LD}$ (type 1) or $\dot{M}_{\rm OAR}$ (type 2)

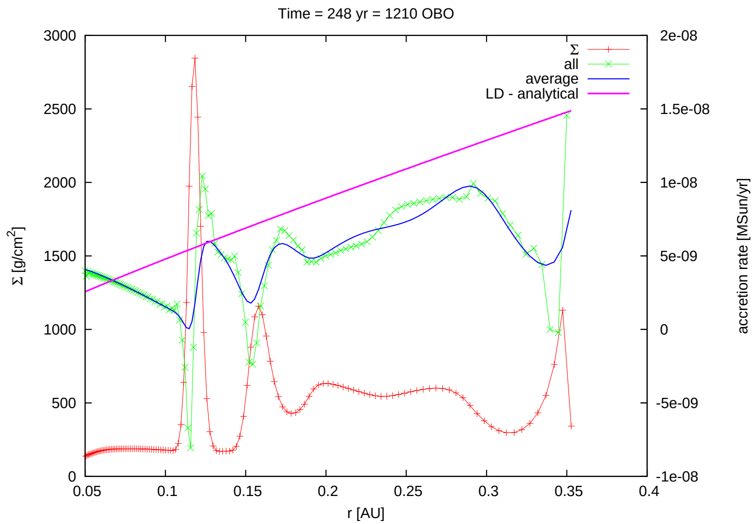
Type 1: Inner disk models

b=0.1; non-zero viscosity in the dead zone

- oscillations of the inner edge of DZ
- growing amplitude
- critical surface density exceeded several times



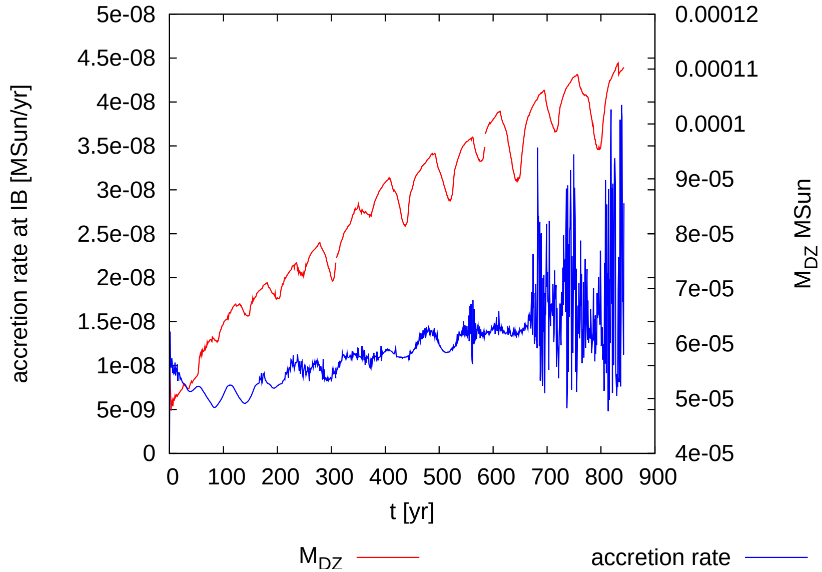
b=0; no viscosity in the dead zone



- dead zone decomposes into rings
- in rings $\dot{M}$ rises steeply with r $\Rightarrow$ mass accumulates in rings

Type 2: Whole-DZ models

- $\alpha = 0.01$, $b = 0.1$, $\dot{M}_{\rm OAR} = 2 \times 10^{-8}\ M_\odot\, yr^{-1}$
- **total mass in DZ grows**
- **mini-outbursts have small effect on** $\dot{M}$



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