Evolution of viscous protoplanetary disk with convective regions

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Pavlyuchenkov et al., ARep (2020)
Maksimova et al., ARep (2020)

15-16th December, 2020

Is the convection an important process in protostellar disks?

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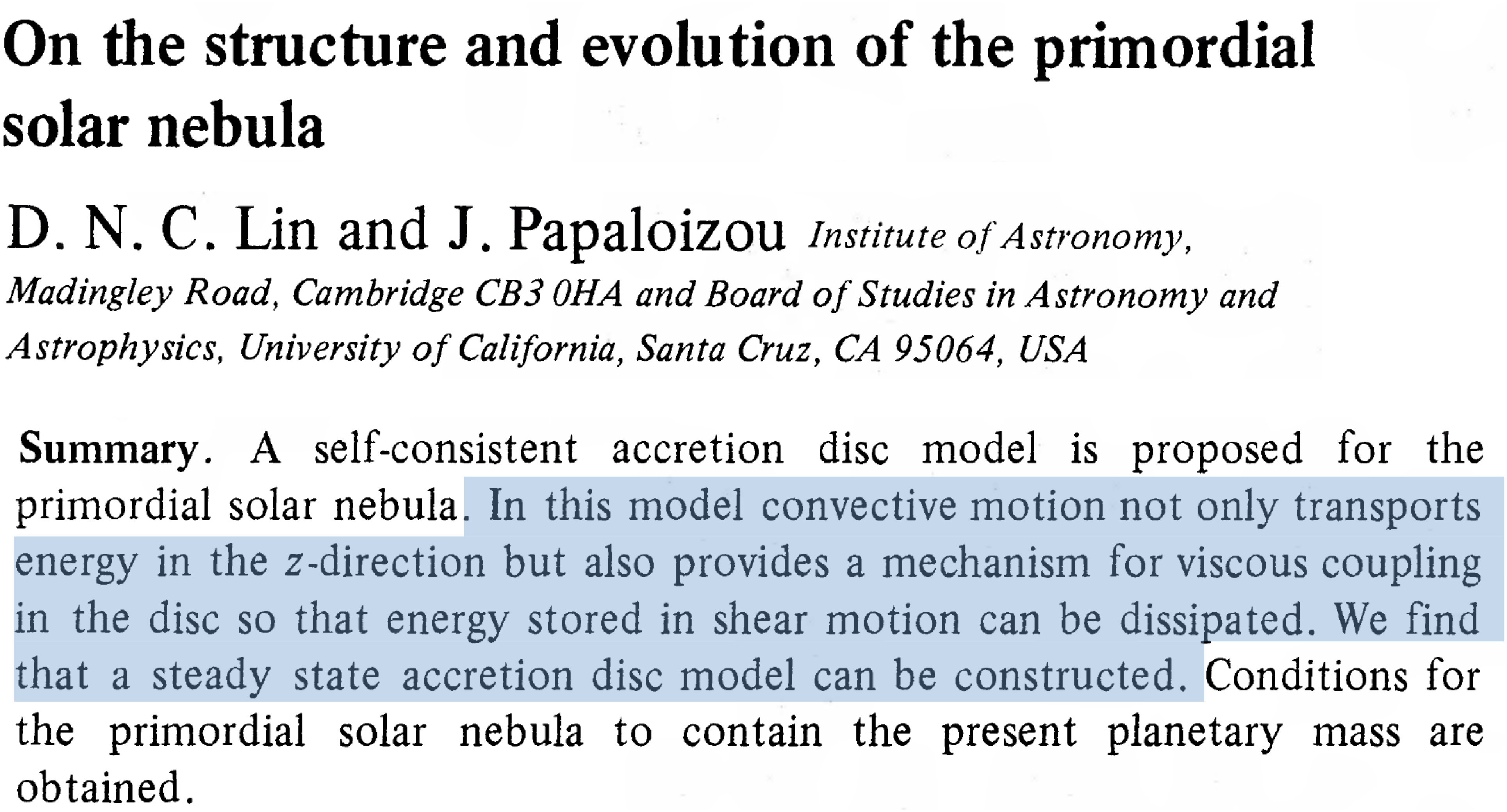

On the structure and evolution of the primordial solar nebula

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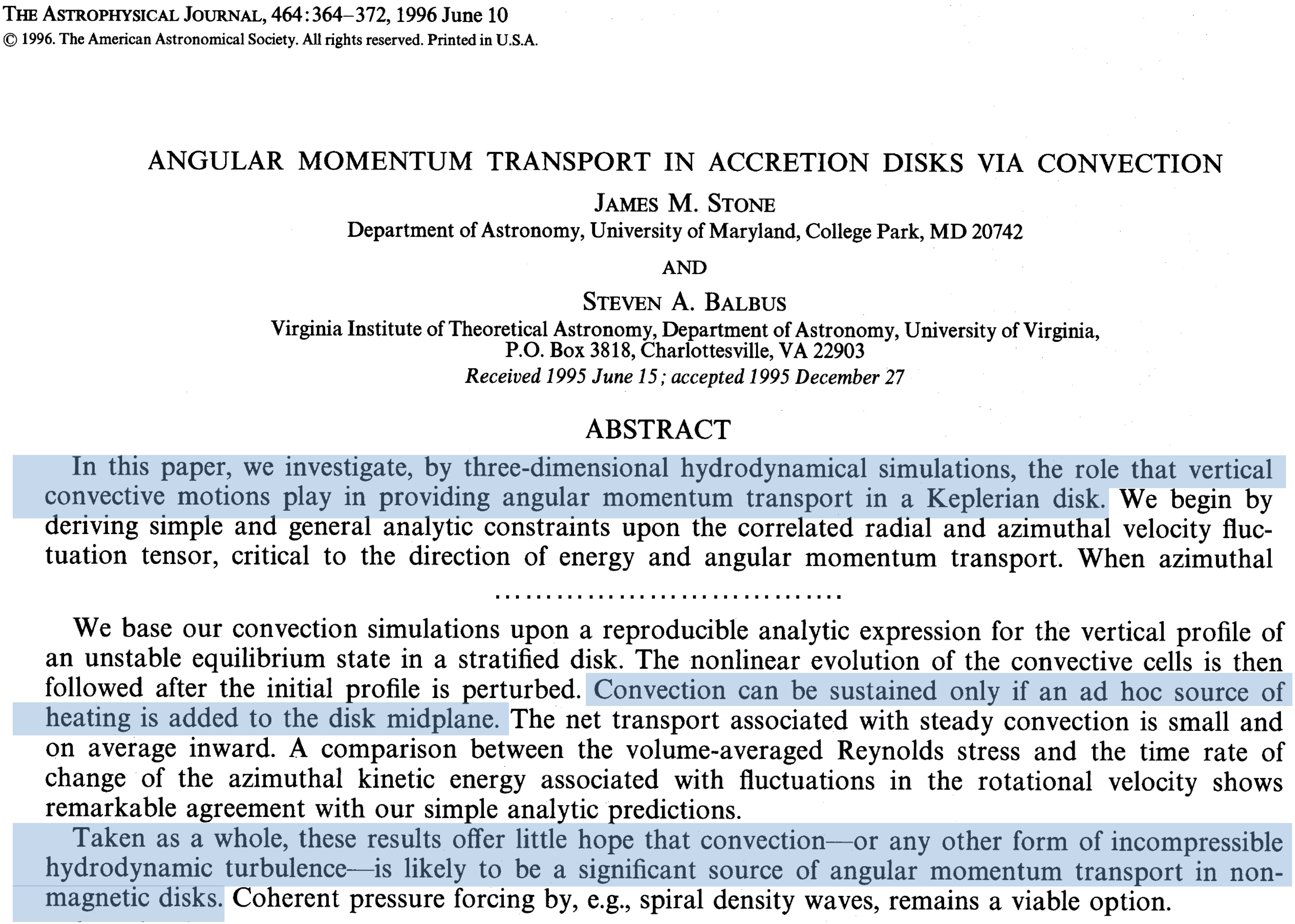
Summary. A self-consistent accretion disc model is proposed for the primordial solar nebula. In this model convective motion not only transports energy in the *z*-direction but also provides a mechanism for viscous coupling in the disc so that energy stored in shear motion can be dissipated. We find that a steady state accretion disc model can be constructed. Conditions for the primordial solar nebula to contain the present planetary mass are obtained.

Is the convection an important process in protostellar disks?



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ANGULAR MOMENTUM TRANSPORT IN ACCRETION DISKS VIA CONVECTION

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ABSTRACT

In this paper, we investigate, by three-dimensional hydrodynamical simulations, the role that vertical convective motions play in providing angular momentum transport in a Keplerian disk. We begin by deriving simple and general analytic constraints upon the correlated radial and azimuthal velocity fluctuation tensor, critical to the direction of energy and angular momentum transport. When azimuthal

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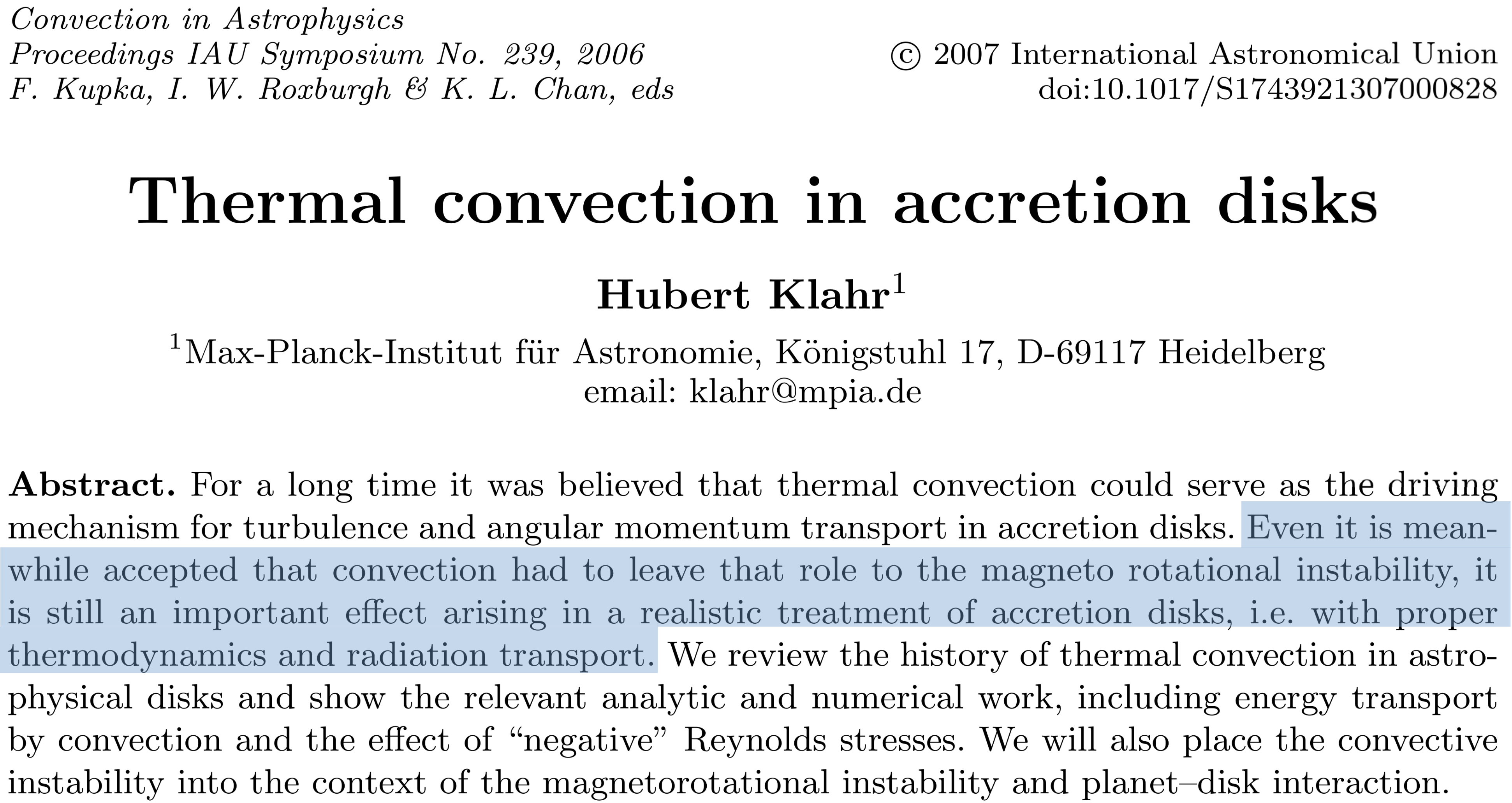
We base our convection simulations upon a reproducible analytic expression for the vertical profile of an unstable equilibrium state in a stratified disk. The nonlinear evolution of the convective cells is then followed after the initial profile is perturbed. Convection can be sustained only if an ad hoc source of heating is added to the disk midplane. The net transport associated with steady convection is small and on average inward. A comparison between the volume-averaged Reynolds stress and the time rate of change of the azimuthal kinetic energy associated with fluctuations in the rotational velocity shows remarkable agreement with our simple analytic predictions.

Taken as a whole, these results offer little hope that convection—or any other form of incompressible hydrodynamic turbulence—is likely to be a significant source of angular momentum transport in non-magnetic disks. Coherent pressure forcing by, e.g., spiral density waves, remains a viable option.

Is the convection an important process in protostellar disks?



Convection in Astrophysics
Proceedings IAU Symposium No. 239, 2006
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Thermal convection in accretion disks

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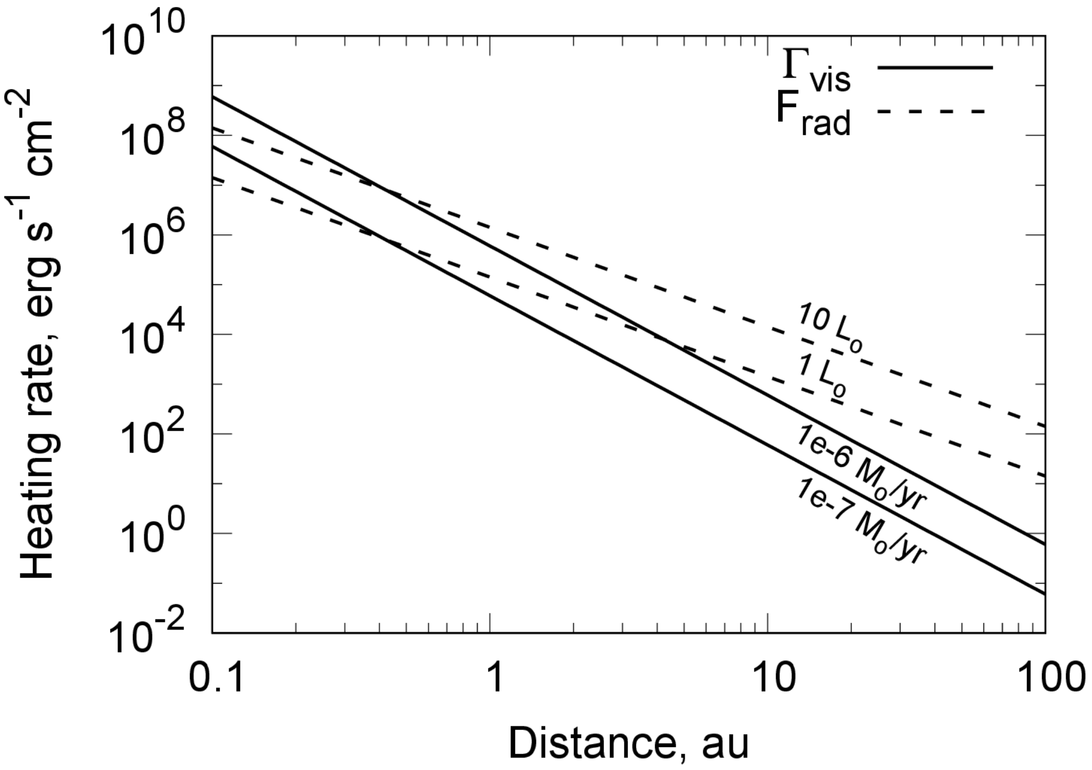
Abstract. For a long time it was believed that thermal convection could serve as the driving mechanism for turbulence and angular momentum transport in accretion disks. Even it is meanwhile accepted that convection had to leave that role to the magneto rotational instability, it is still an important effect arising in a realistic treatment of accretion disks, i.e. with proper thermodynamics and radiation transport. We review the history of thermal convection in astrophysical disks and show the relevant analytic and numerical work, including energy transport by convection and the effect of "negative" Reynolds stresses. We will also place the convective instability into the context of the magnetorotational instability and planet–disk interaction.

Why should we expect convection to operate in protostellar disks?

1. The volume heating due to accretion (viscous dissipation) can be comparable to surface heating by stellar radiation at R < 10 AU

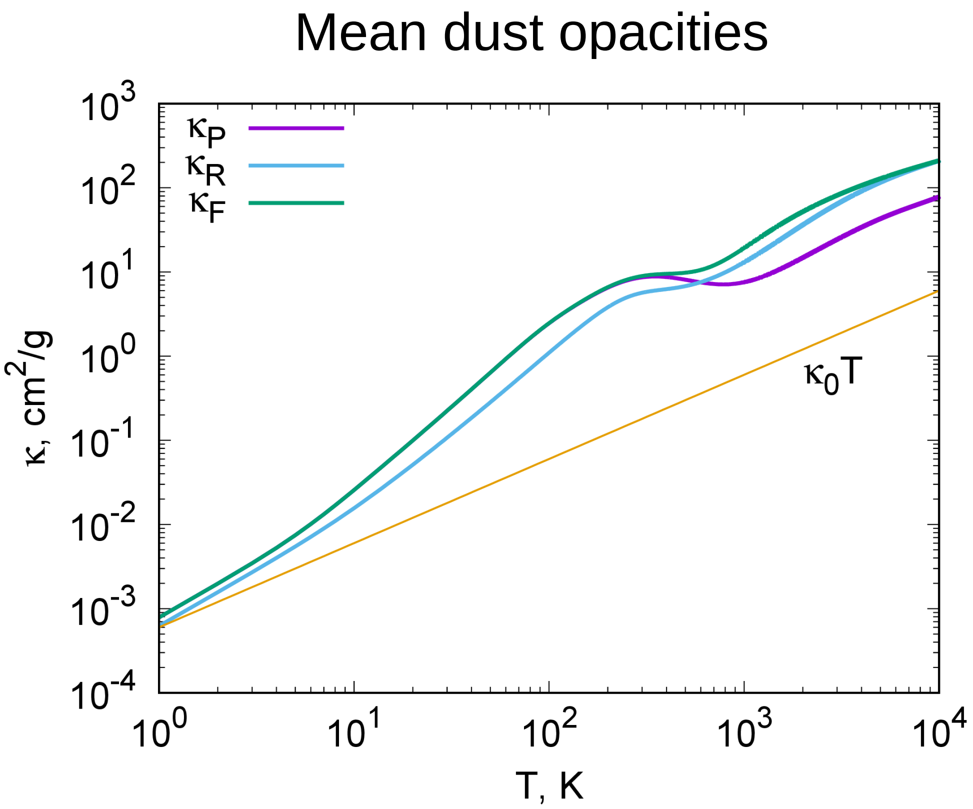


$$\Gamma_{\rm vis} = \frac{3}{4\pi}\frac{GM_*\dot{M}}{R^3}$$

$$F_{\rm rad} = \frac{\mu L_*}{4\pi R^2}$$

Why should we expect convection to operate in protostellar disks?

2. The mean opacity (determined by dust) is the growing function of temperature


Mean dust opacities

Condition of convective instability:

$$\nabla \equiv \frac{d\log T}{d\log P} \geqslant \frac{\gamma - 1}{\gamma}$$

$$\nabla \approx \frac{1}{4-\beta}$$

$$\kappa = \kappa_0 T^{\beta}$$

optically thick disk
to its own IR

$$\boxed{\beta \gtrsim 1} \quad \text{for } \gamma = 3/2$$

Lin & Papaloizou, MNRAS (1980)

Our model

The evolution of axially-symmetrical, geometrically thin, Keplerian disk without radial pressure gradients is prescribed by the Pringle equation:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[\sqrt{R}\frac{\partial}{\partial R}\left(\nu\sqrt{R}\Sigma\right)\right] + W$$

where *W(R,t)* is the infall rate of gas from envelope. The viscosity dissipation rate (per unit surface):

$$\Gamma_{\rm vis} = \frac{9}{4}\frac{GM_*}{R^3}\nu\Sigma$$

Pringle, ARAA (1981)

The evolution of such disk is controlled by the radial profile of viscosity coefficient.

In our model, total viscosity is given by:

$$\nu = \nu_{\mathrm{bg}} + \tilde{\nu}_{\mathrm{c}}$$

ν_{bg} – background viscosity which provides continuous gas accretion

$\tilde{\nu}_{\mathrm{c}}$ – convective viscosity which depends on the convection parameters at given radius

Key and most dangerous assumption:
Convection evolves into turbulence which acts as viscosity

$$\nu = \boxed{\nu_{\mathrm{bg}}} + \tilde{\nu}_{\mathrm{c}}$$

Background viscosity is provided by some undefined mechanism (such as magneto-rotational or vertical shear instability)

We describe the background viscosity phenomenologically with the power law:

$$\nu_{\mathrm{bg}} = \nu_0 \left(\frac{R}{R_{\mathrm{AU}}} \right)^p$$

where parameters $\nu_0 = 10^{15} \mathrm{cm}^2 \mathrm{s}^{-1}$ and $p = 1$ are selected to reproduce surface density profiles and accretion rates towards observed protoplanetary disks:

$$\Sigma \propto R^{-1}$$
$$\dot{M} \sim 10^{-7} M_{\odot}/\mathrm{yr}$$

Williams et al. A&A (2011)
Hartmann et al. ApJ (1998)

$$\nu = \nu_{\mathrm{bg}} + \boxed{\tilde{\nu}_{\mathrm{c}}}$$

Convective viscosity is non-zero in convectively unstable regions, it is introduced as:

$$\nu_{\mathrm{c}} = \gamma\, H V_{\mathrm{c}},$$

γ – the fraction of mass in convectively unstable region

H – disk height

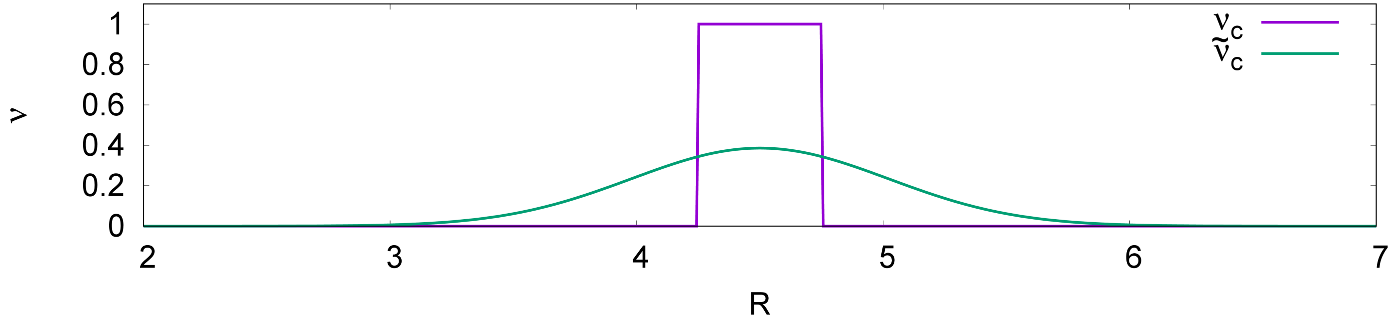
V_{c} – velocity of convective elements (eddies)

Velocity of convective eddies is found assuming that the whole viscous heating is transferred into the flux of kinetic energy:

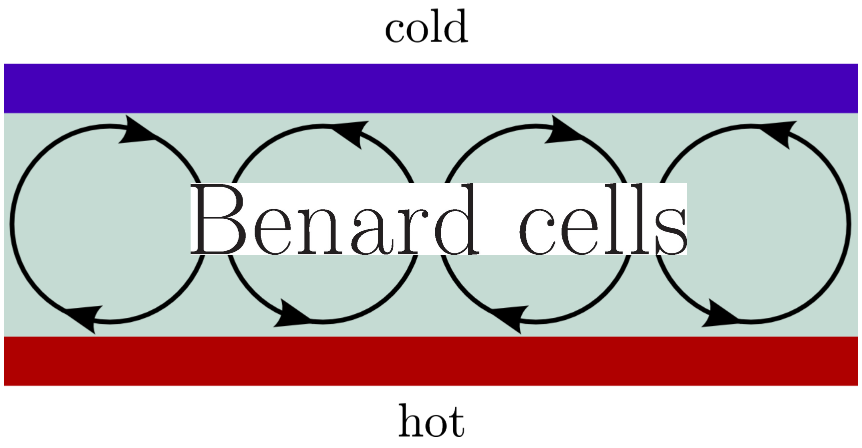
$$\frac{\rho_0\, V_c^3}{2} = \Gamma_{\mathrm{vis}}$$

The resulting distribution of convective viscosity is additionally smoothed over the radius using the Gaussian function of width *H*:

$$\tilde{\nu}_{\mathrm{c}}(R) = \frac{\int\limits_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} \nu_{\mathrm{c}}(r) \mathrm{e}^{-\frac{(R-r)^2}{2H^2}} dr}{\int\limits_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} \mathrm{e}^{-\frac{(R-r)^2}{2H^2}} dr}$$

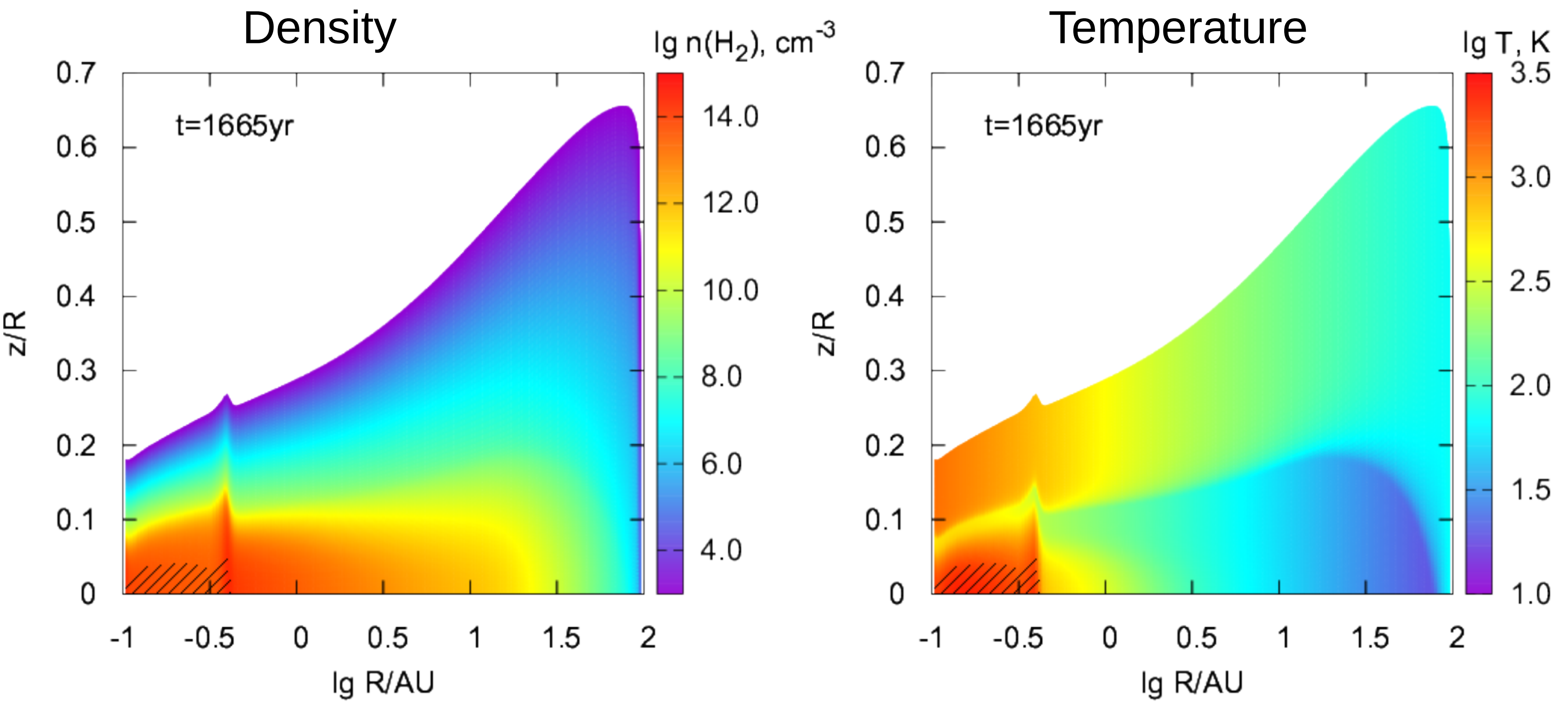


We assume that the radial extent of convective region should not be smaller than the disk height



Identification of convective regions: $\frac{dT}{dz} < -\frac{g(z)}{c_P}$

Reconstruction of vertical disk structure with radiative transfer model



The ordinate is the ratio of the height above the equator to the radial distance to the star.

Convectively unstable regions are hatched

Identification of convective regions: Calculation of vertical disk structure

UV heating and viscous heating

$$S = S_{\rm star} + S_{\rm bg} + \frac{\Gamma_{\rm vis}}{\Sigma}$$

$$S_{\rm star} = \frac{L_*}{4\pi r^2}\kappa_{\rm uv}\,\exp\left(-\tau_{\rm star}/\mu\right)$$

$$S_{\rm bg} = D\,\sigma T_{\rm bg}^4\,\kappa_{\rm uv}\,\exp\left(-2\tau_{\rm bg}\right)$$

Diffusion of IR radiation

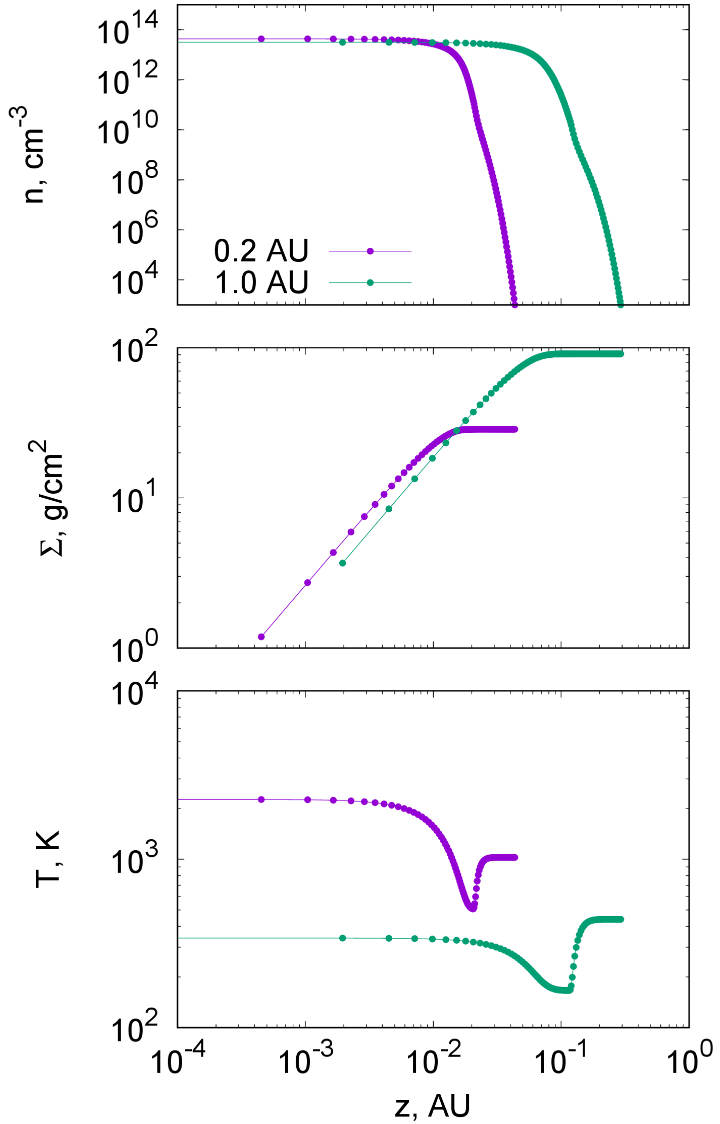
$$c_{\rm V}\frac{\partial T}{\partial t} = \kappa_{\rm P}c(E - aT^4) + S$$

$$\frac{\partial E}{\partial t} - \frac{\partial}{\partial z}\left(\frac{c}{3\rho\kappa_{\rm R}}\frac{\partial E}{\partial z}\right) = -\rho\kappa_{\rm P}c(E - aT^4)$$

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{GM_*}{r^3}z - 2\pi G\Sigma$$

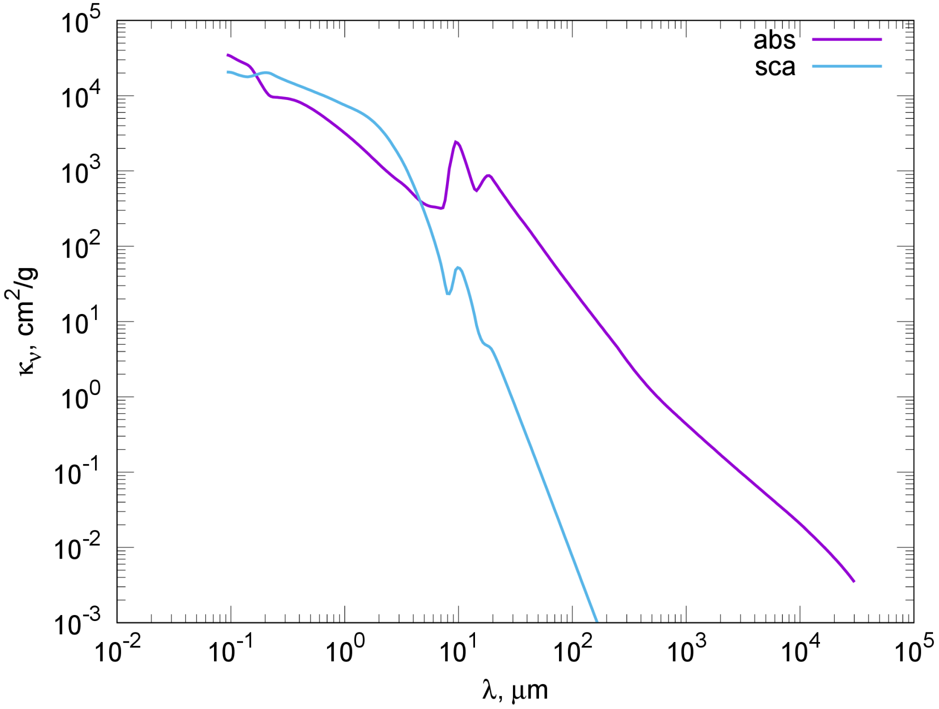
Distributions of density and temperature in z-direction



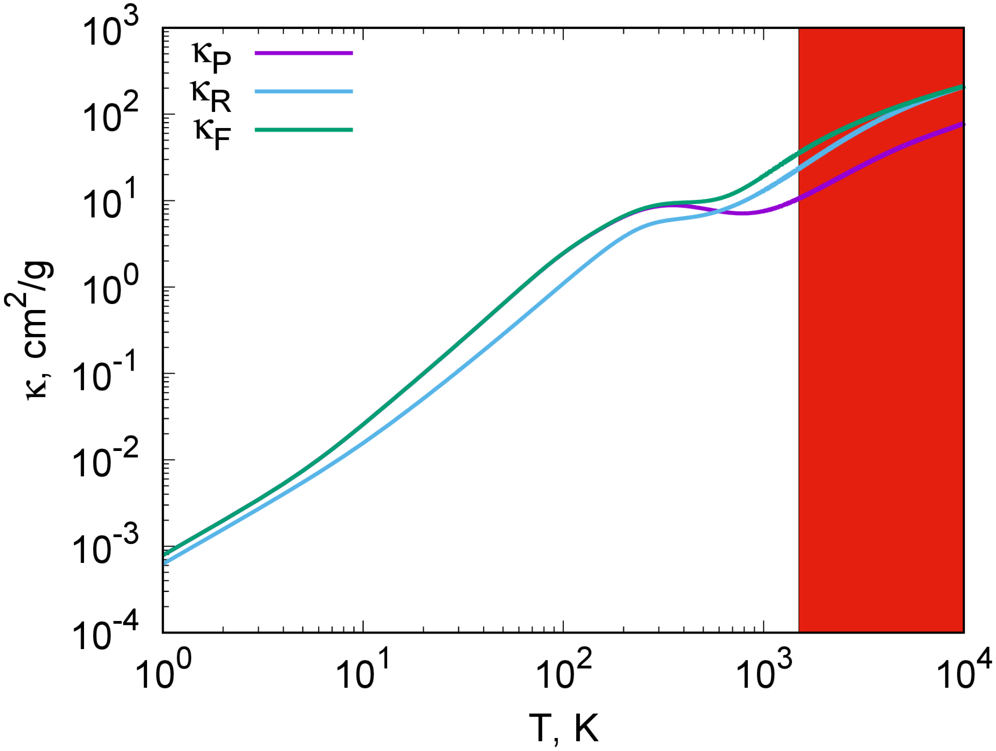
Vorobyov & Pavlyuchenkov, A&A(2017)

Important ingredient of the radiative transfer model is the use of realistic dust opacities

Frequency-dependent absorption and scattering coefficients



Temperature-dependent Planck and Rosseland opacities



Red bar is the temperature range where opacities are not appropriate due to the dust evaporation

Parameters of the disk feeding (setup of *W(R,t)*):

Constant infall rate from envelope onto disk:

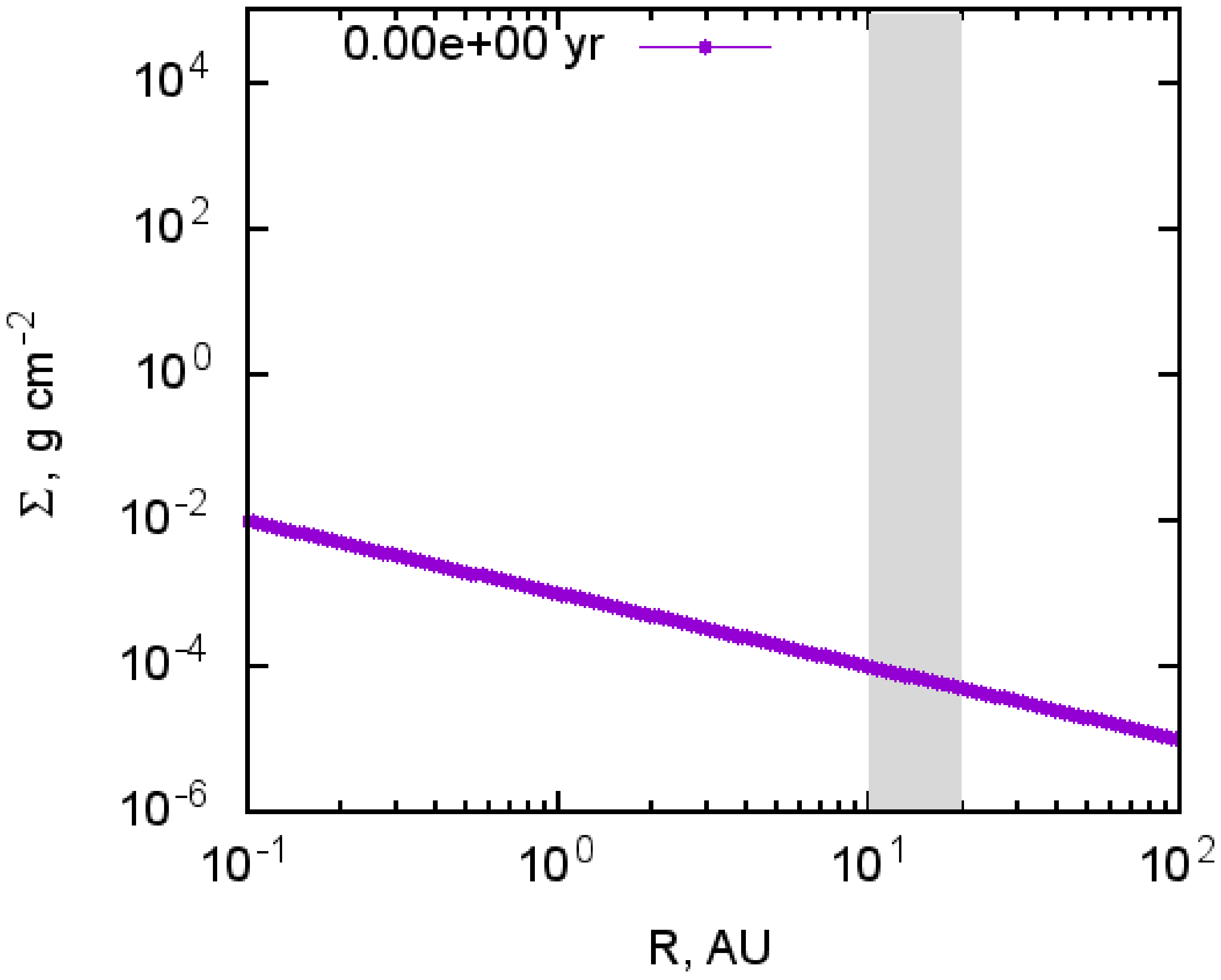
$\dot{M} = 10^{-7} M_{\odot}/\mathrm{yr}$ in a ring 10 – 20 AU

$$W(R,t) = \frac{\dot{M}}{\pi \left(R_{\mathrm{out}}^2 - R_{\mathrm{in}}^2\right)}$$

With this setup we are not interested in long-term disk evolution but in accretion pattern at initial stages

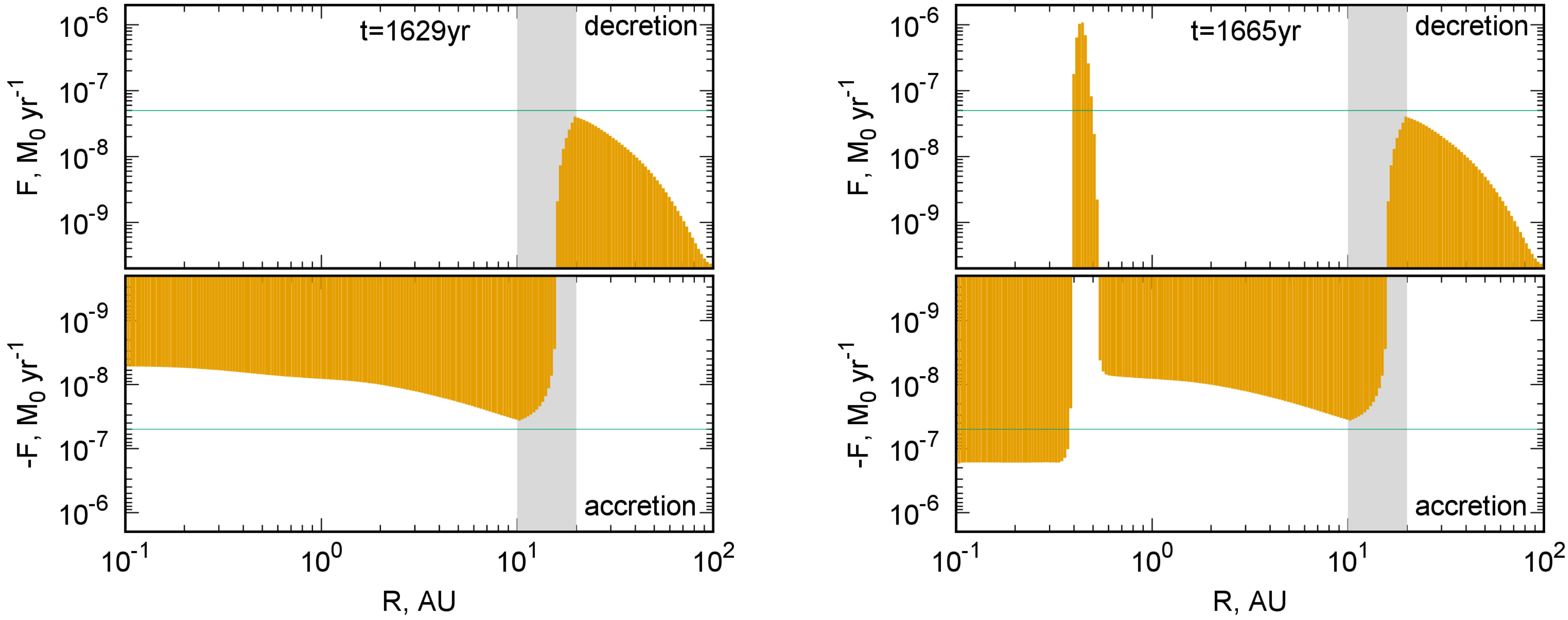
Model results

Evolution of surface density distribution



The region of infall from envelope is shown with gray bar

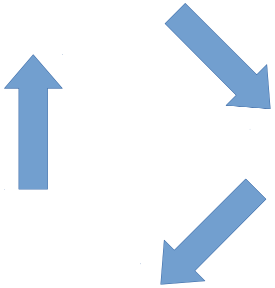
Radial distributions of accretion-decretion flux


Before outburst

During outburst

The positive value of the flux (the upper part of each distribution) corresponds to the flow from the star, the negative value (the lower part of the distribution) corresponds to flow towards the star. The vertical bar shows the area of gas accretion from the envelope.

Development of convection in a disk is the process with positive feedback



Increase of viscous heating

Increase of temperature gradient 1/g*dT/dz

Gain of convective instability

Criteria for convective instability:

$$\frac{dT}{dz} < -\frac{g(z)}{c_P}$$

Estimation:

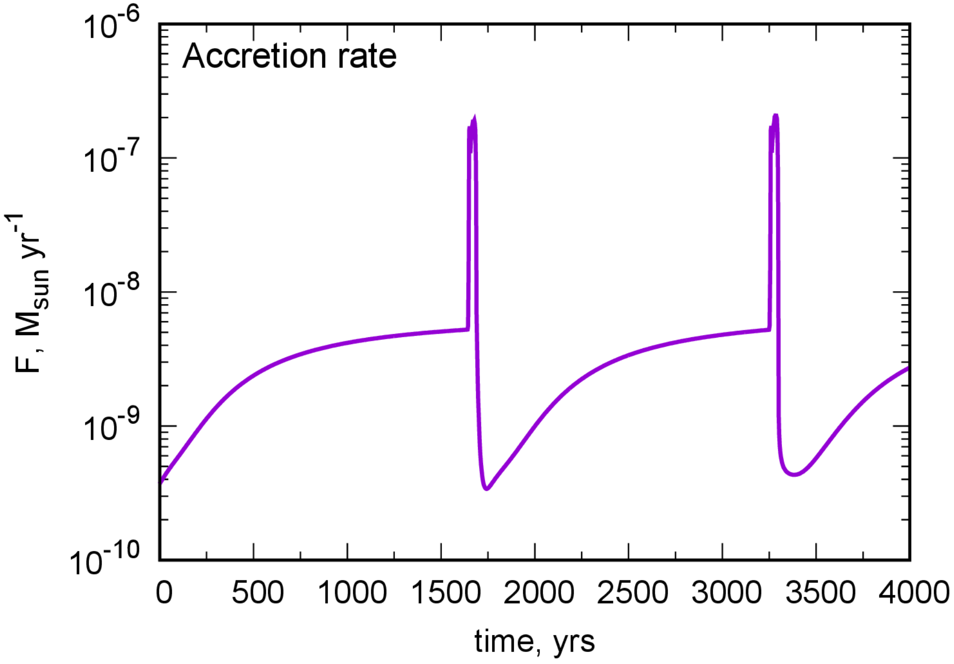
$$T_{\rm surf}^4 = \frac{16}{3}\frac{T_{\rm mid}^4}{\Sigma\kappa_0 T^\beta}$$

$$g = \Omega_K^2 H \qquad \frac{H}{R} = \frac{c_s}{V_K}$$

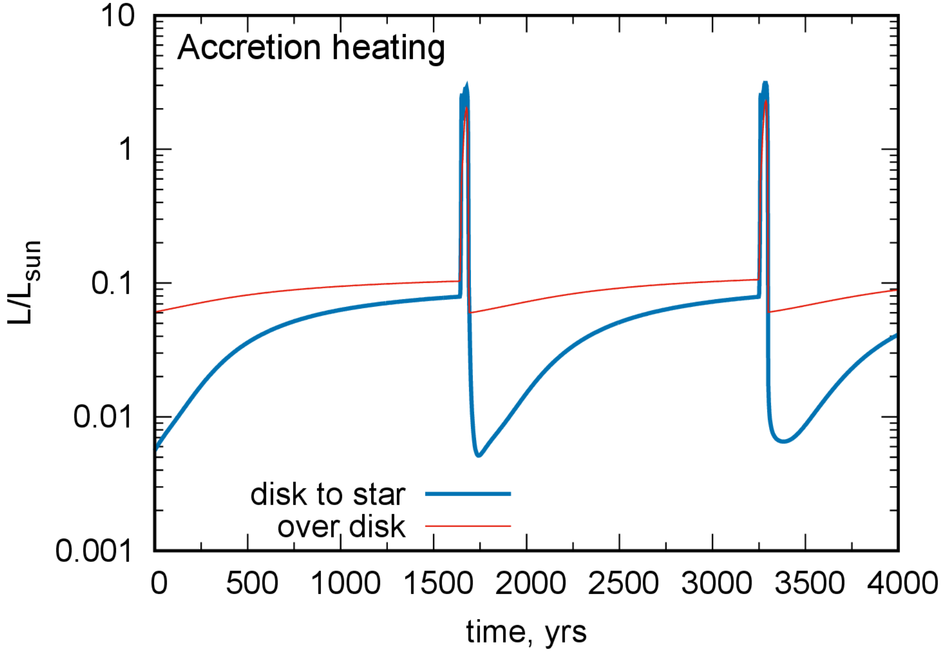
In our model, convection is self-sustaining only for short periods in the inner regions of the disk, while the role of background viscosity is important for ensuring its launch

The evolution of accretion rate and luminosity after establishment of a episodic accretion mode

Accretion rate

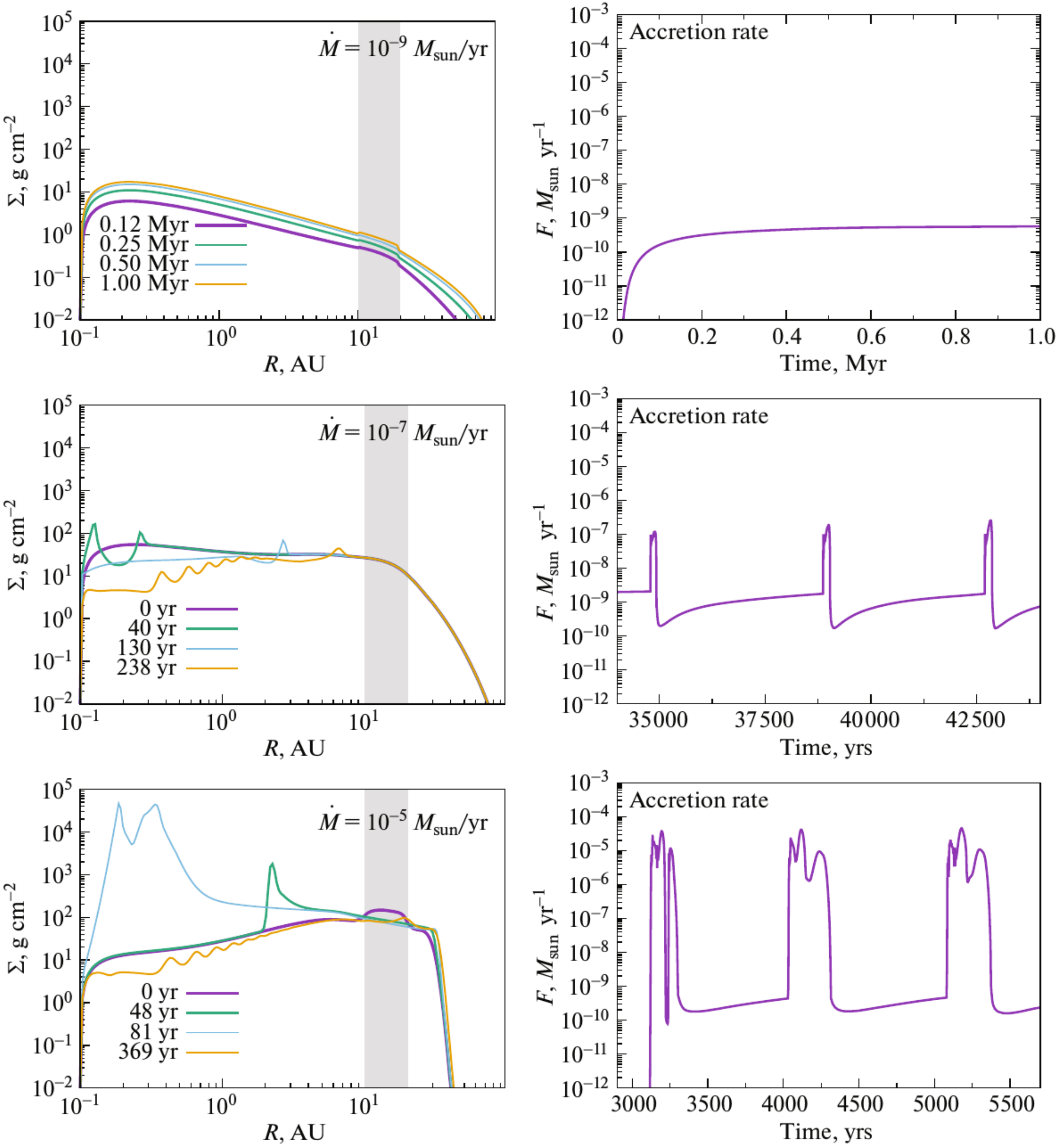


Accretion luminosity

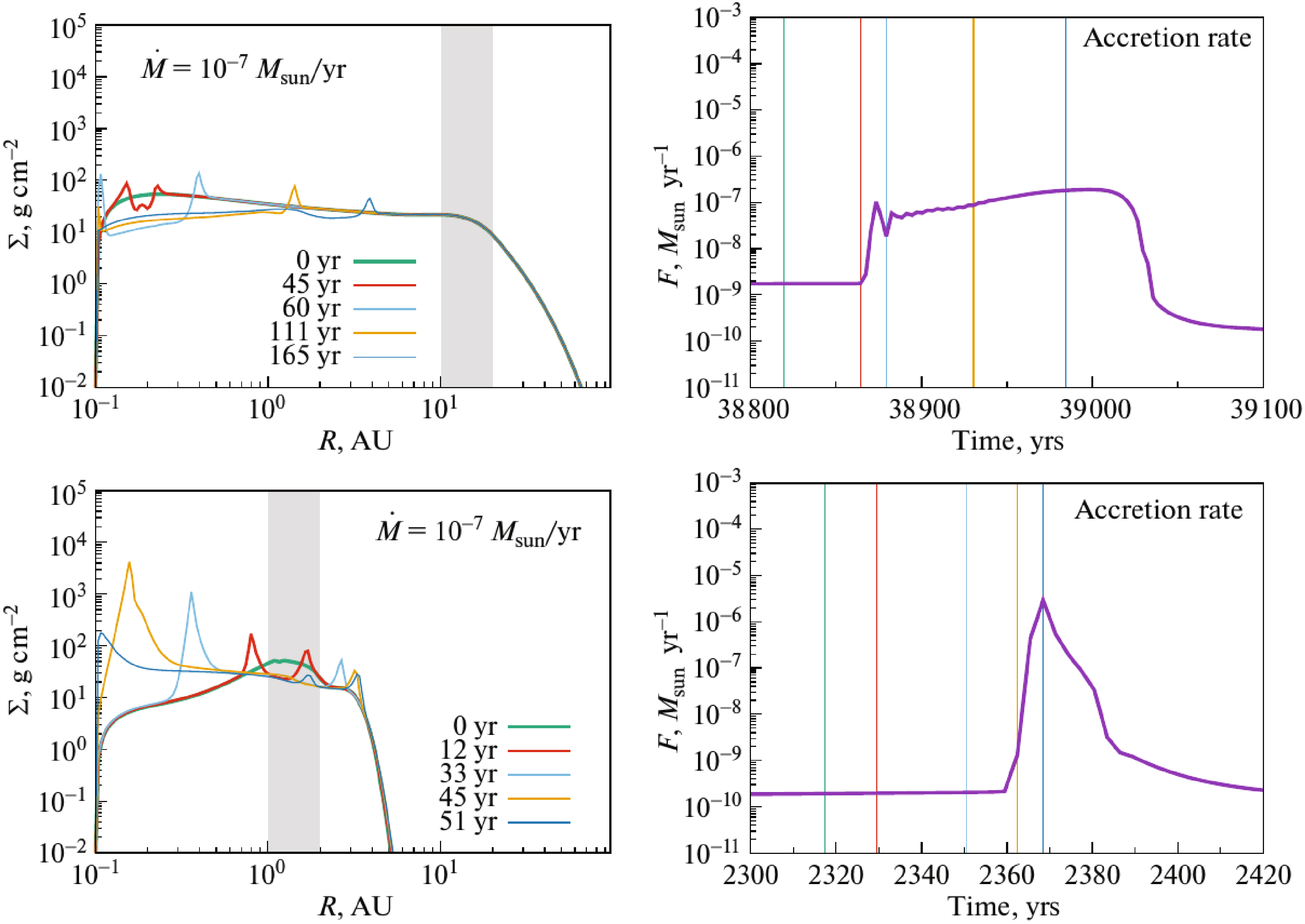


Thin red line corresponds to accretion luminosity of the entire disk. Thick blue line shows the luminosity which is associated with accretion of gas onto the star from the inner disk edge.

Surface density and accretion rate evolution at different mass inflow

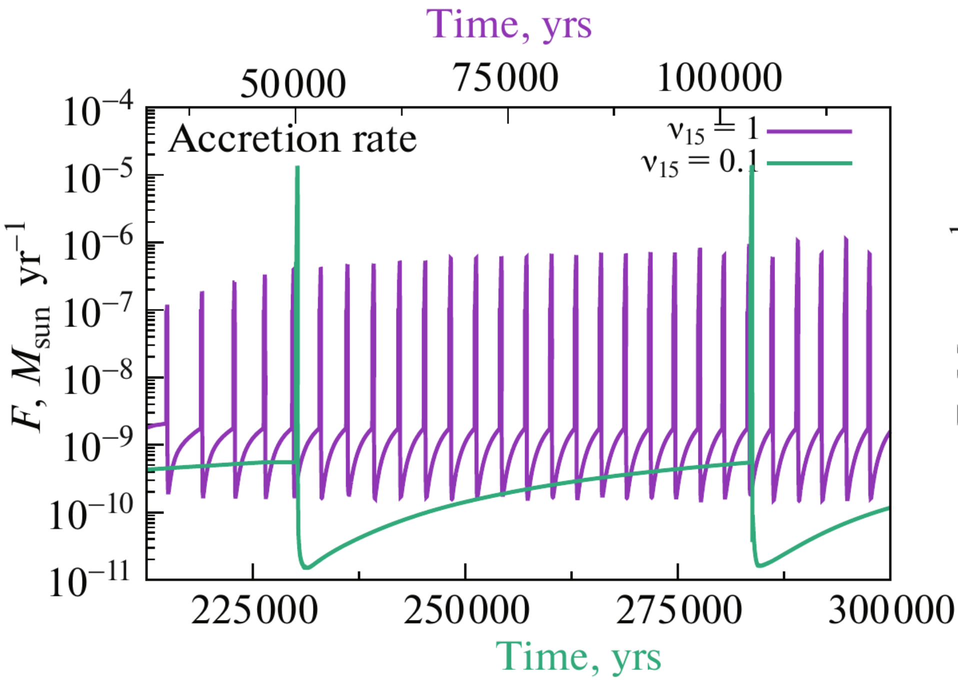


Inside-out and outside-in bursts in convectively unstable disks

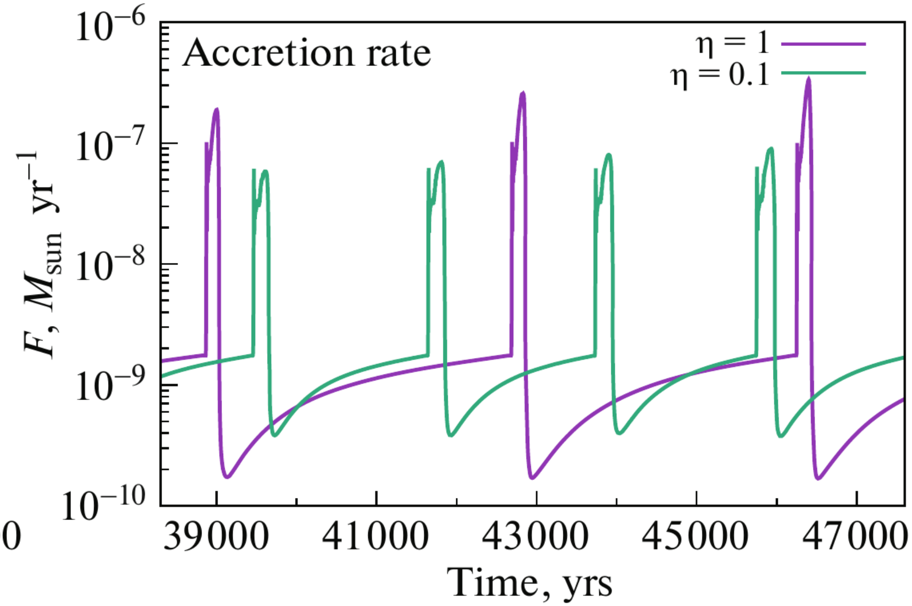


Burst appearance at different model parameters

Varied background viscosity



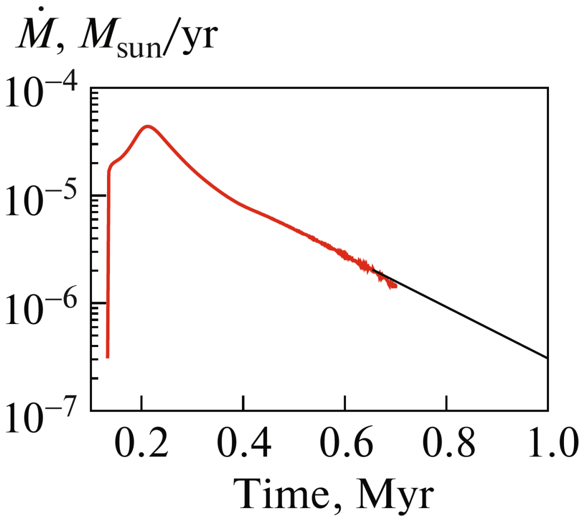
Varied convection efficiency



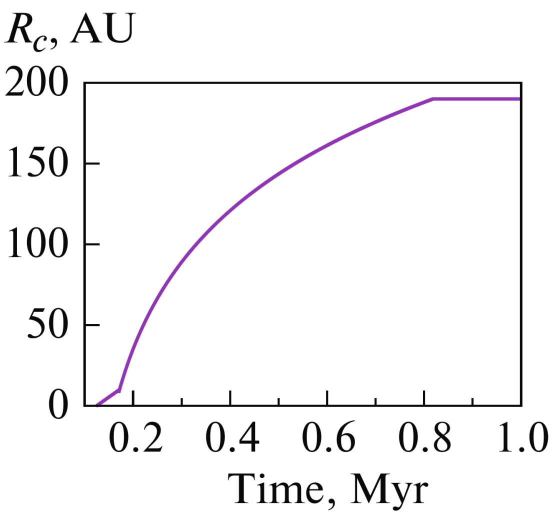
$$\frac{\rho_0 V_c^3}{2} = \eta \Gamma_{\mathrm{vis}}$$

Disk model with decremental matter inflow from the envelope

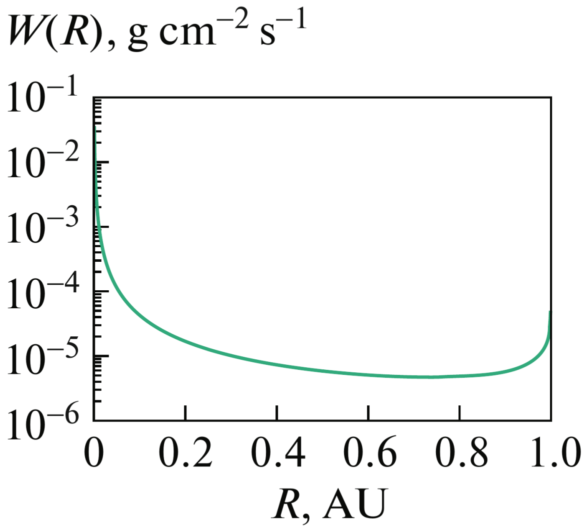
Total accretion rate



Centrifugal radius



Accretion rate per unit area



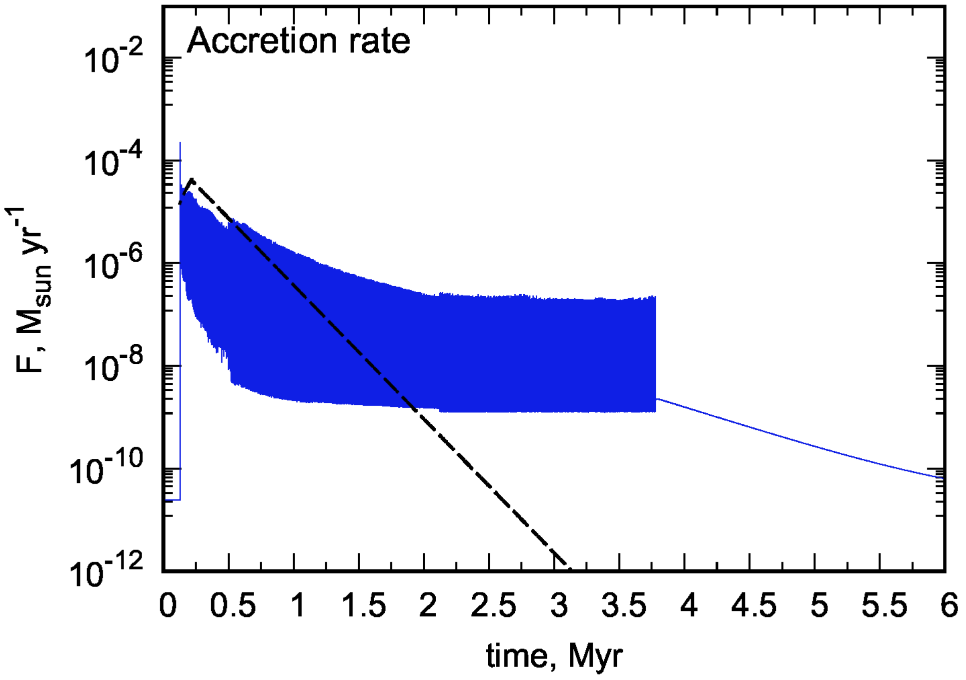
Time- and position-dependent feeding function *W(R,t)*:

$$W(R,t)=\frac{\dot{M}(t)}{8\pi R_c^2(t)}\left(\frac{R}{R_c(t)}\right)^{-3/2}\left[1-\left(\frac{R}{R_c(t)}\right)^{1/2}\right]^{-1/2}$$

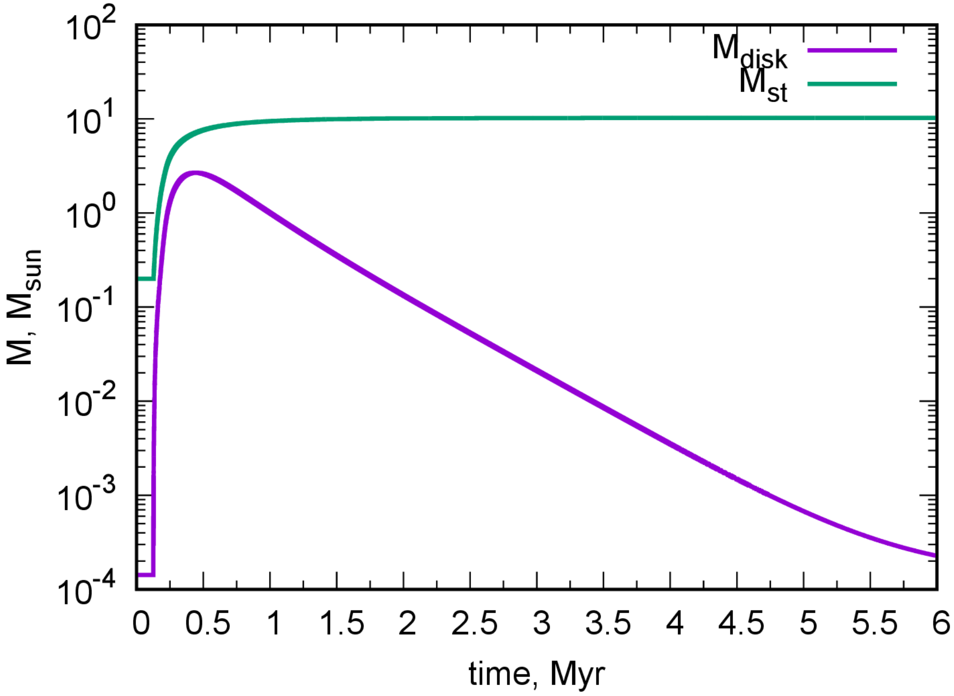
Hueso & Guillot, A&A (2005)
Pavlyuchenkov et al., ARep(2015)

Accretion history for a disk with decremental matter inflow from the envelope

The numerous bursts merge into
a single continuous blue band.

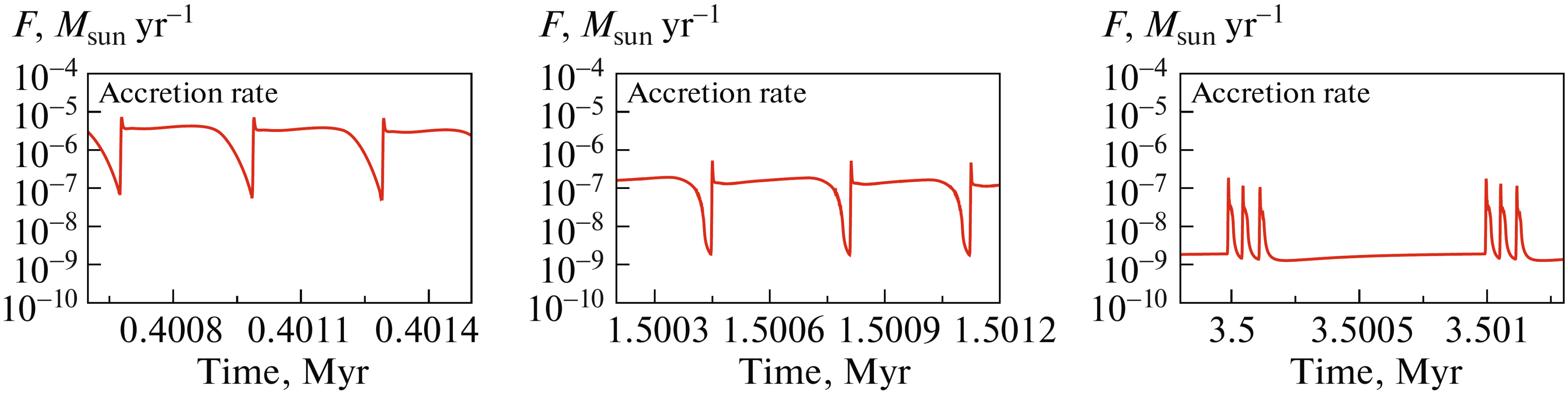


Pretty massive system!



In the first million years, the disk accumulates considerable mass, and the subsequent disk evolution is defined by the redistribution of this mass rather than by accretion from the envelope, which becomes negligible.

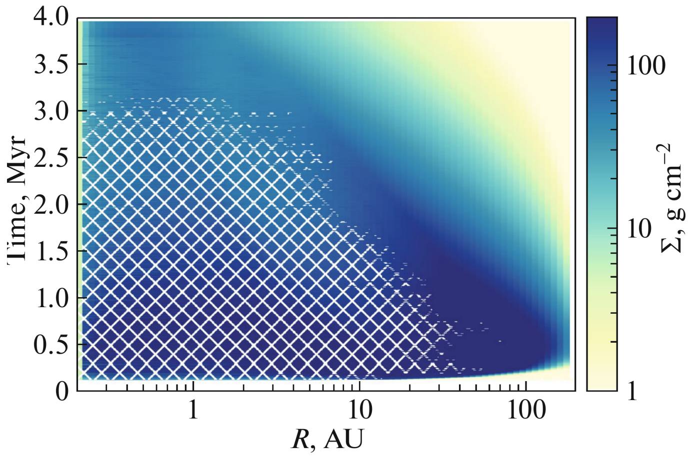
Accretion curves at different evolution times



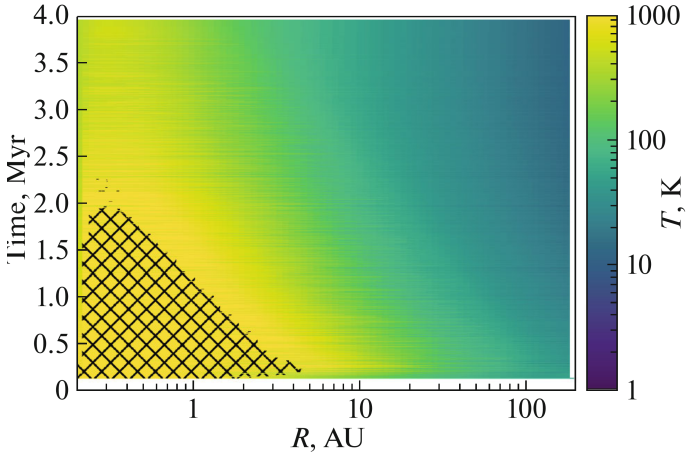
Burst parameters (intensity, duration, frequency), as well as their shape, change with time, which is associated with a change in the disk mass and the integral flow of matter through it. The bursts may take very bizarre shapes.

Long-term evolution of radial surface density and temperature distributions

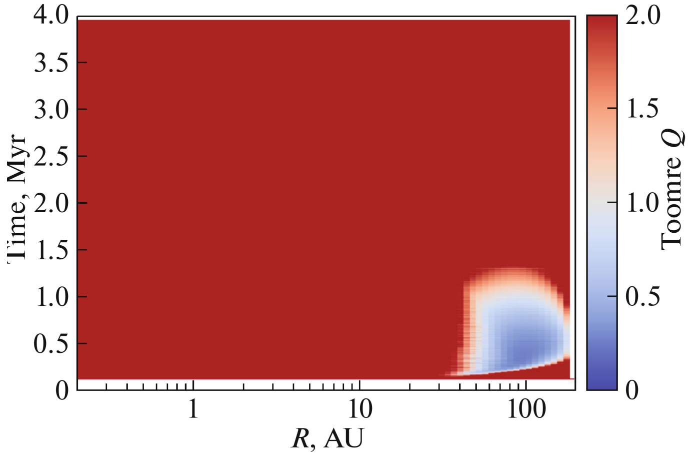
The disk quickly becomes convectively unstable and remains so for almost 4 Myr. Meanwhile, the instability captures an area of several tens of AU and then gradually decreases.



The crosshatching indicates the regions where temperature exceeded 1500 K at its maximum. At such temperatures the dust evaporation must be important.



Disk is gravitationally unstable at initial times of the evolution (t < 0.5 Myr) in the disk’s outer parts (R > 50 AU).



Conclusions

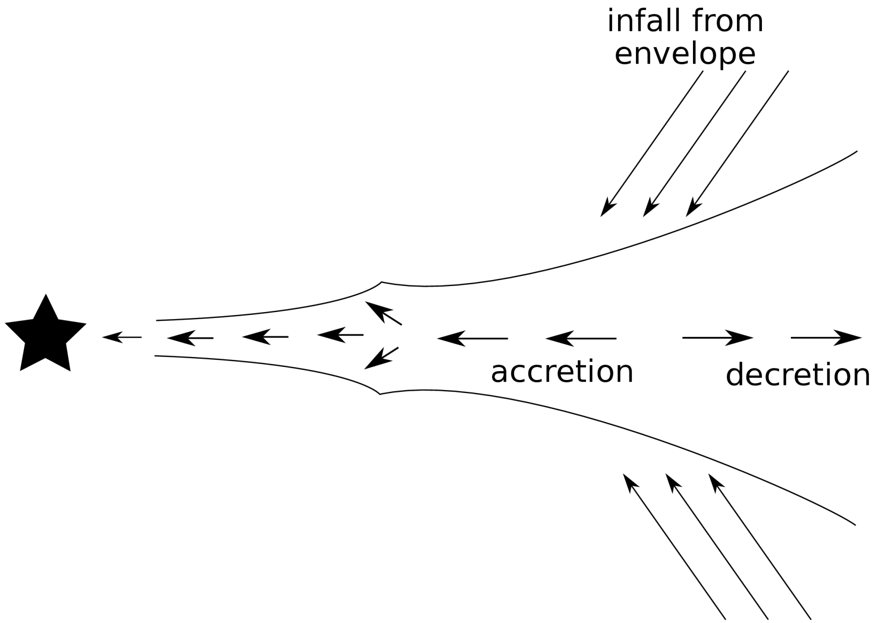
1. The presented model is rather illustrative because of the many underlying physical assumptions. Its main purpose is to demonstrate the possible role of convection as a driver of episodic accretion in protostellar disks.

2. The presented picture need to be supported by more detailed hydrodynamic simulations coupled with the theory of turbulence driven by convection.

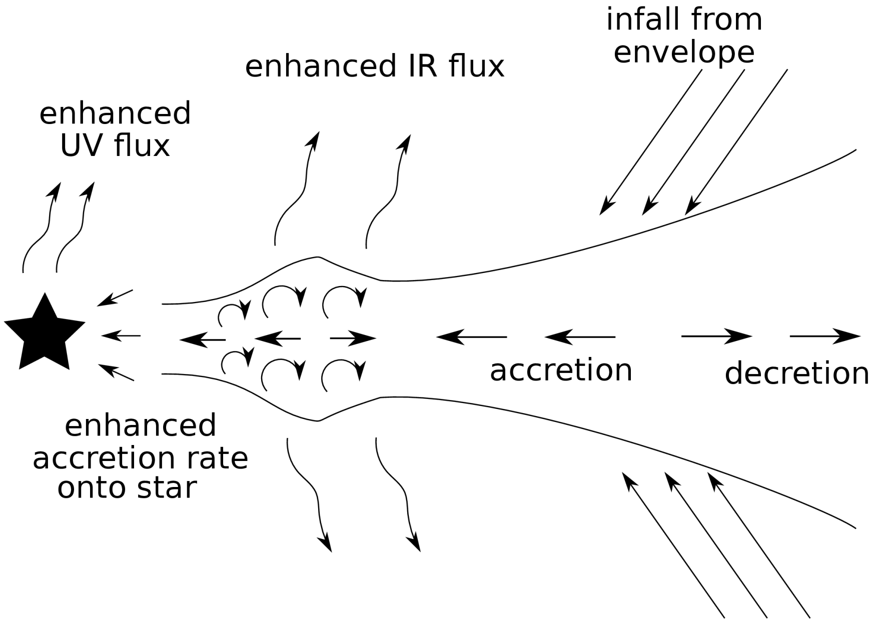
More slides

Scheme of the episodic accretion mode in a protoplanetary disk

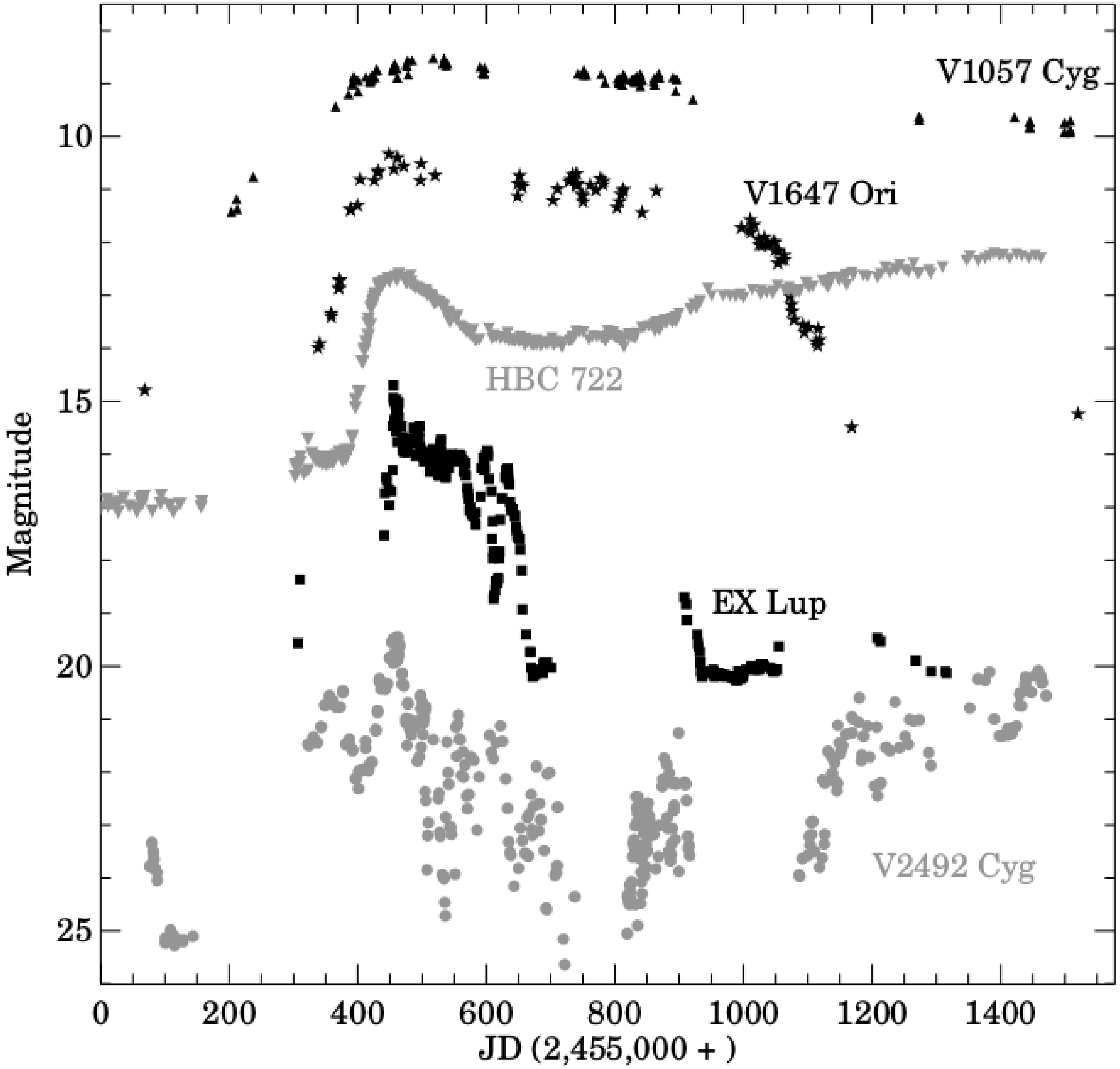
Accumulation phase



Outburst phase



Variety of flaring young stellar objects



Audard et al., PPVI (2014)

Estimation of the centrifugal radius for prestellar core L1544

Density profile:

$$n = \frac{n_0}{1 + \left(\frac{R}{R_{\rm core}}\right)^2}$$

$$R_{\rm core} = 3 \times 10^3 {\rm AU}$$

$$M_{\rm core} = 1.2 M_\odot$$

$$\Omega = 8 \times 10^{14} {\rm s}^{-1}$$

Centrifugal radius:

$$R_{\rm acc} = \frac{\Omega^2 R_{\rm core}^4}{G M_{\rm core}}$$

$$R_{\rm acc} = 11 {\rm AU}$$

Chacón-Tanarro et al. A&A(2019)
Klapp et al. ApJ(2014)

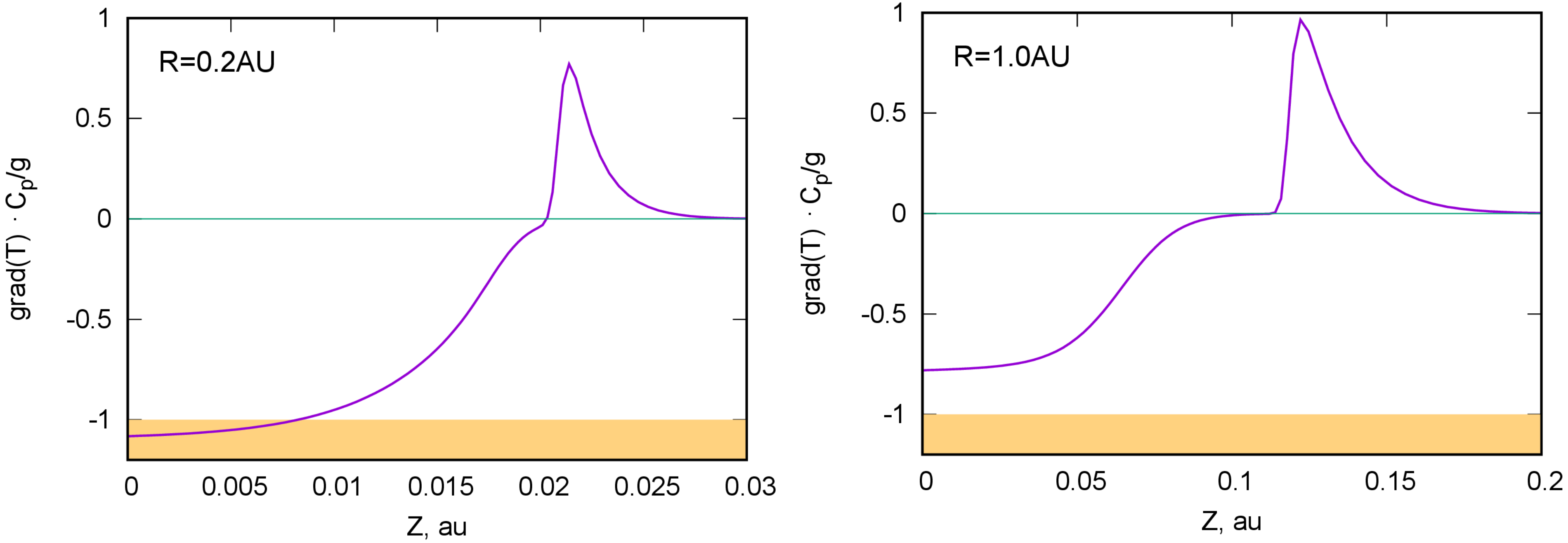
Identification of convectively unstable regions

$$\frac{dT}{dz} < -\frac{g(z)}{c_P}$$

Ratio of temperature gradient to adiabatic gradient as a function of z-coordinate for the flash phase

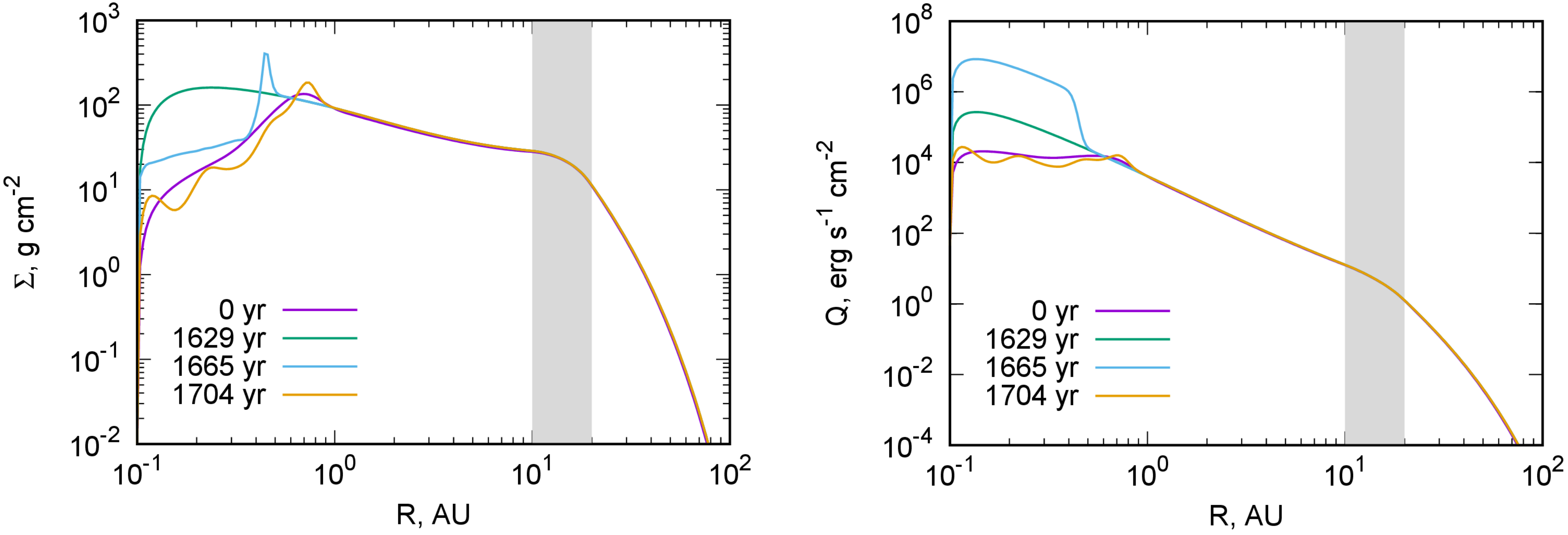
Unstable layer

Stable layer



Convectively unstable region is shown with orange color

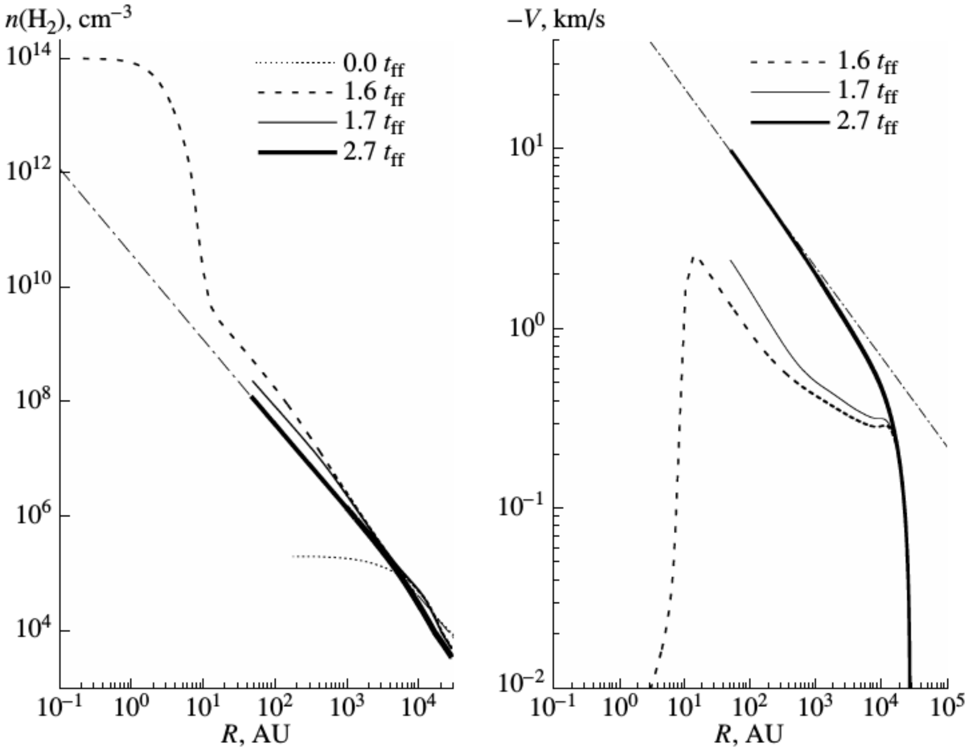
The evolution of surface density and viscous heating rate distributions for several moments illustrating the development of the accretion outbreak



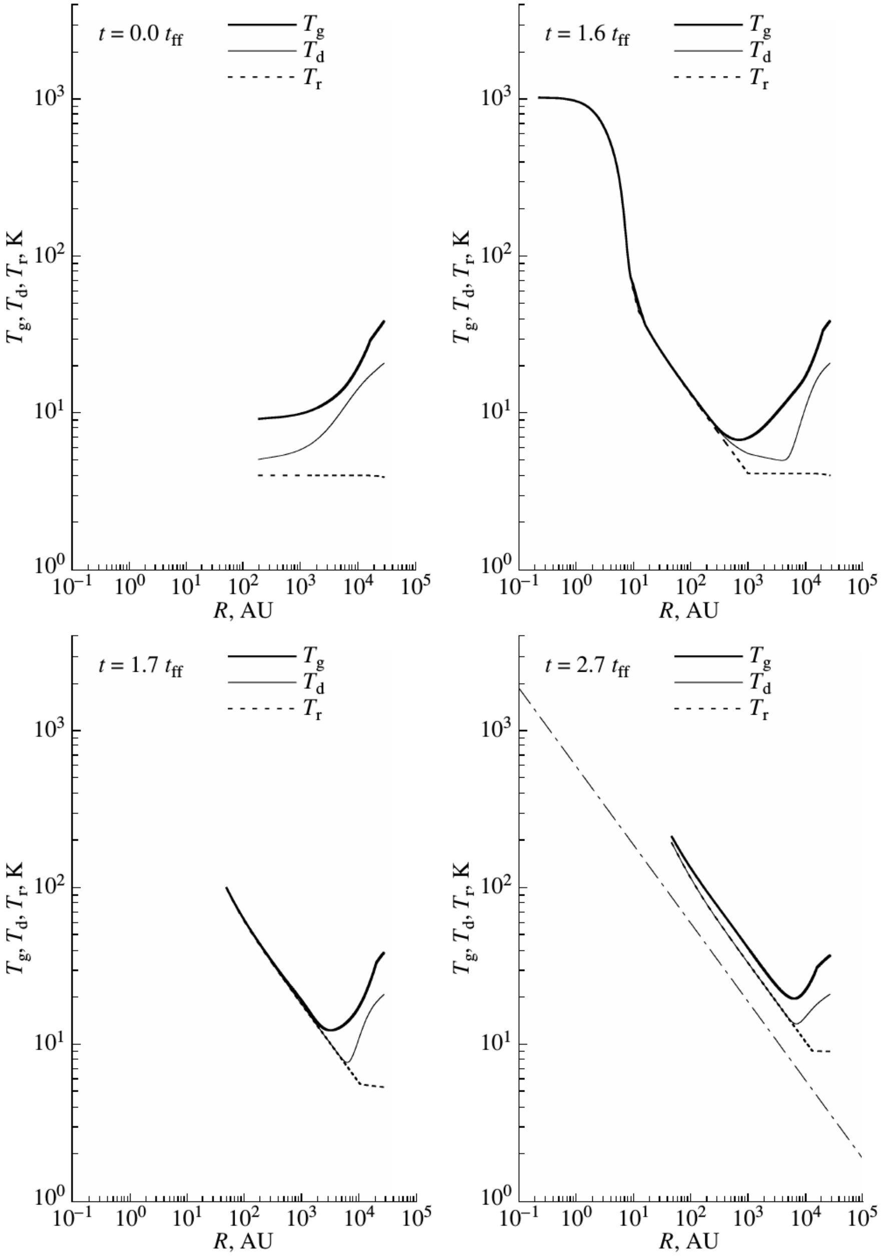
Zero time corresponds to the end of the previous accretion outburst.
Vertical bar shows the area of gas accretion from the envelope.

Core collapse simulations with 1D RHD model

Density and velocity

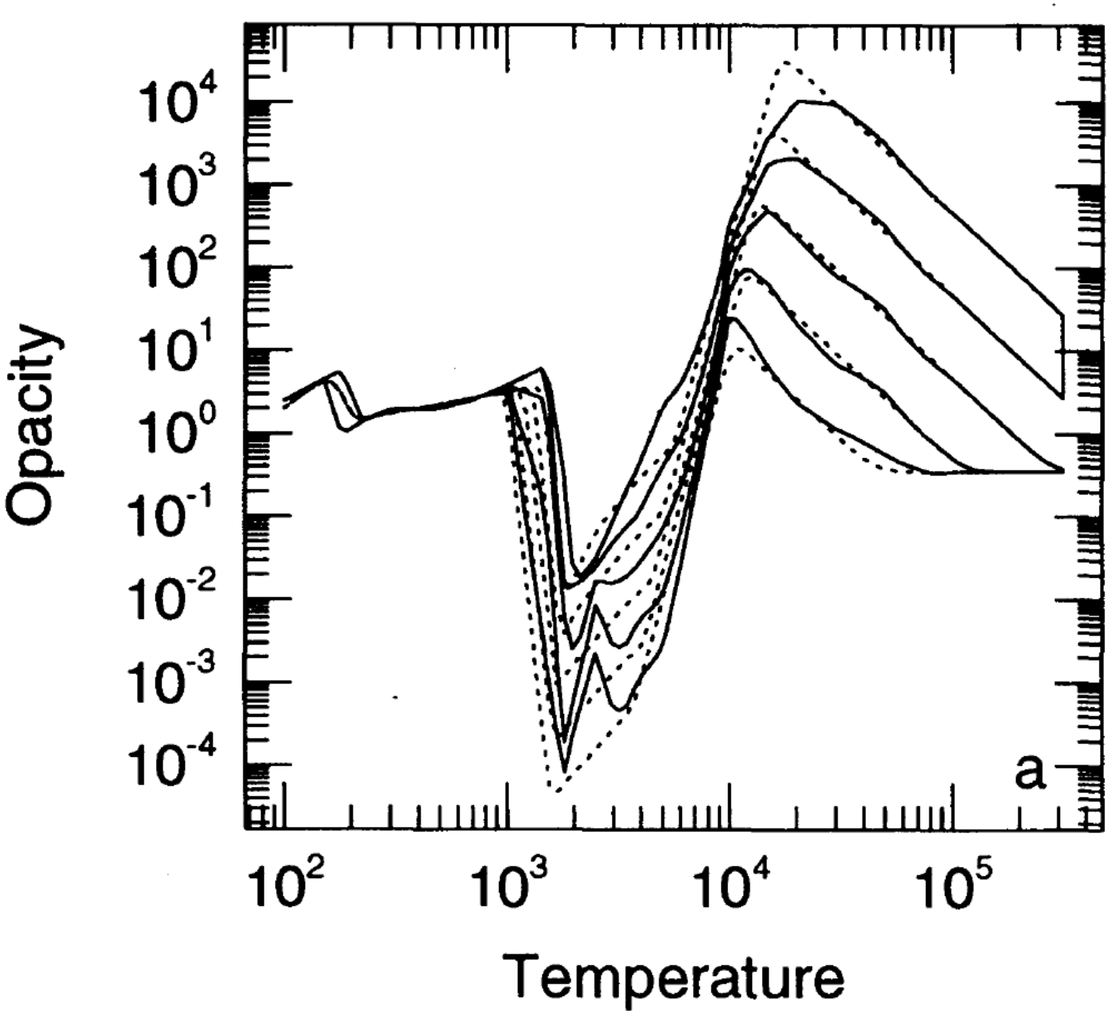


Gas and dust temperatures



Pavlyuchenkov et al., ARep(2015)

Mean opacity as a function of temperature



Bell & Lin (1994)