Two-dimensional models of layered protoplanetary discs

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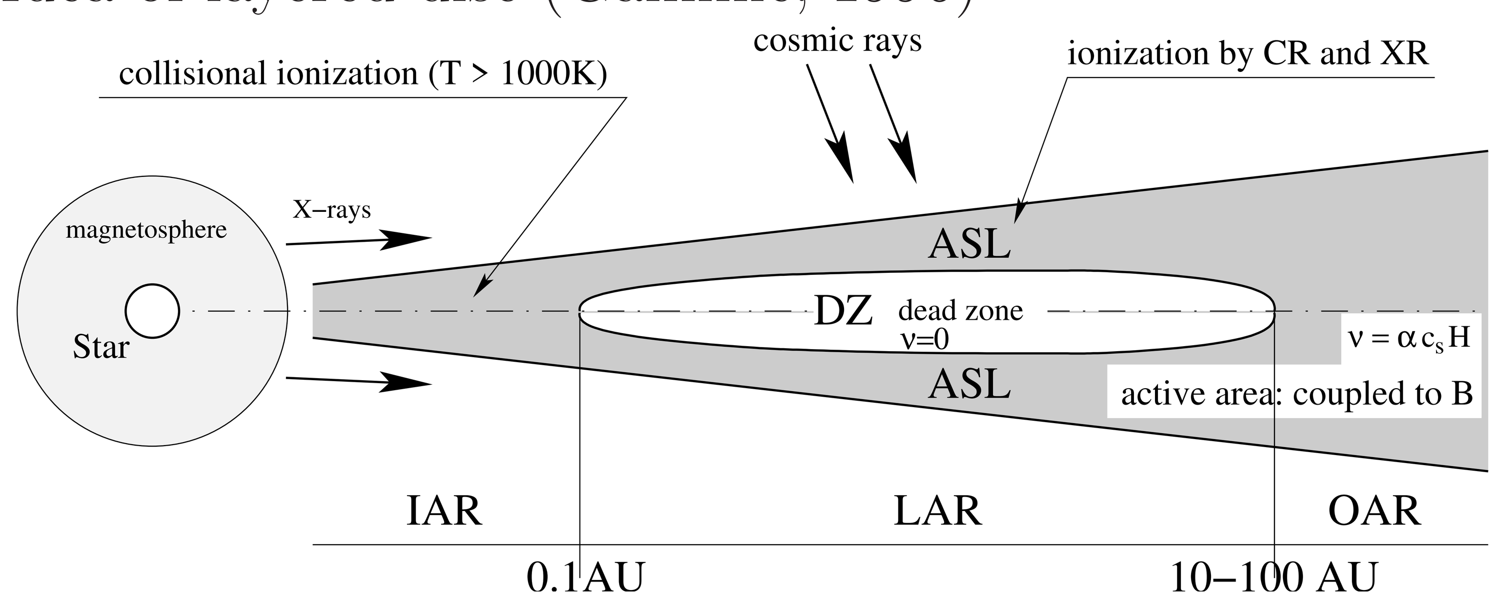
Abstract:

In this work we study two-dimensional axially symmetric models of layered protoplanetary discs using the radiation-hydrodynamic code TRAMP. We follow the accumulation of mass in the dead zone due to the radially varying accretion rate. In some models we allow for a residual viscosity in the dead zone and explore the effect of different viscosity prescriptions.

We found a new type of instability which causes the dead zone to split into rings. This "ring instability" occurs if there is no (or extremely small) residual viscosity in the dead zone. It works due to the positive feedback between the thickness of the dead zone and the mass accumulation rate. We give an analytical description of this instability, taking into account non-zero thickness of the dead zone and deviations from the Keplerian rotational velocity. The analytical model agrees reasonably well with results of numerical simulations. We speculate about the possible role of the ring instability in protoplanetary discs and in the formation of planets.

If the residual viscosity is included, oscillations of dead zone inner boundary occur, accompanied by variations of the accretion rate onto the central star. We provide a simplified analytical description explaining the mechanism of the oscillations. Finally, we find that the residual viscosity enables stationary accretion in large regions of layered discs. Based on results obtained with the help of a simple 1-D hydrocode we identify these regions, and discuss conditions in which layered discs can give rise to FU Orionis phenomena.

Idea of layered disc (Gammie, 1996)

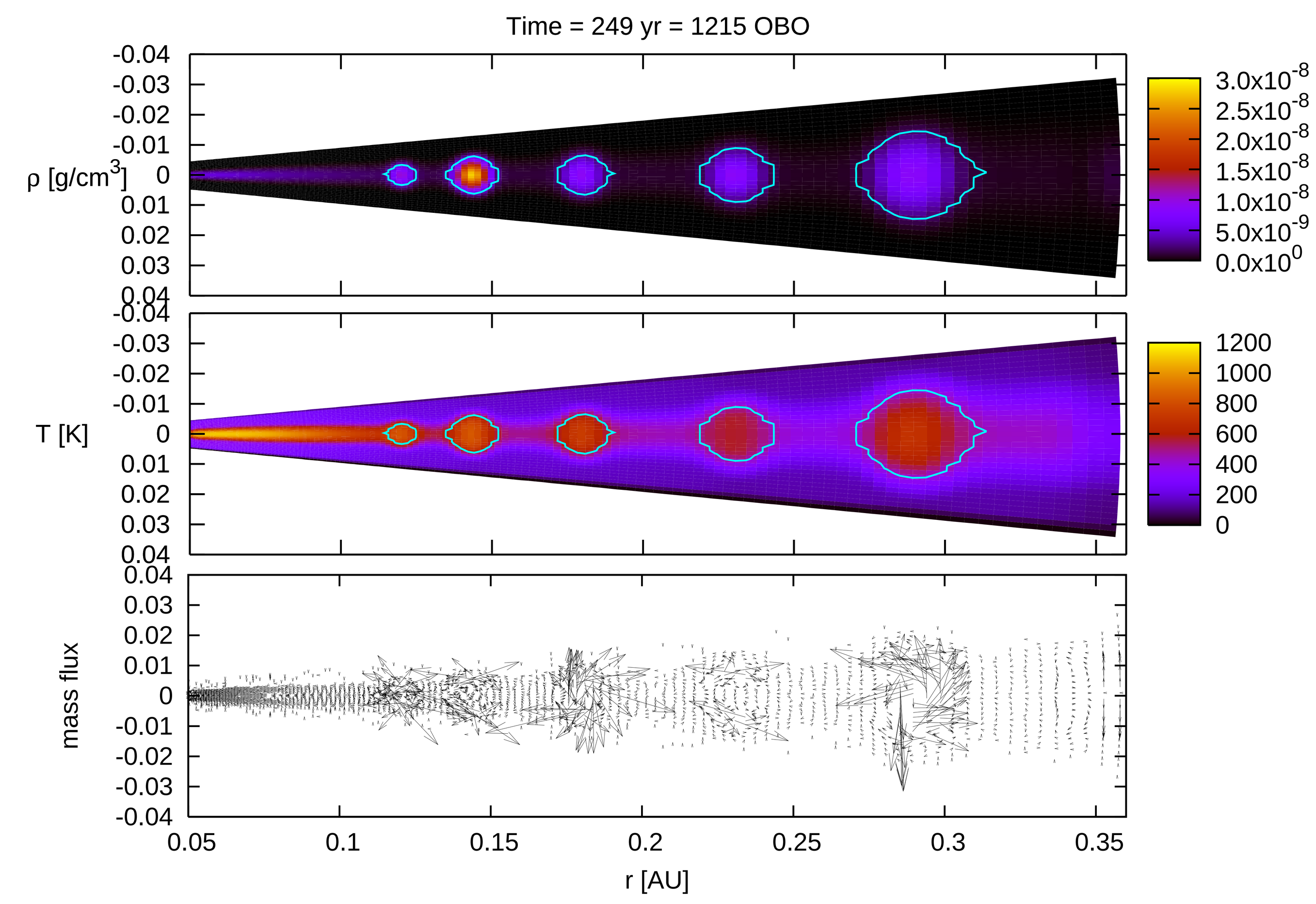


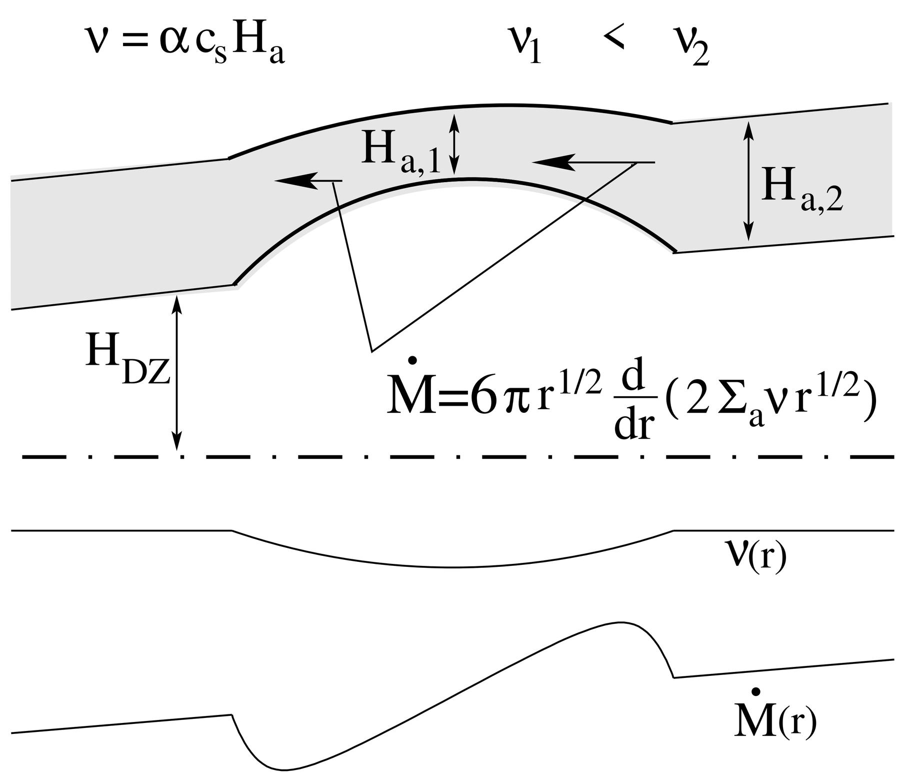
It is believed that the main source of the viscosity in protoplanetary discs is the magnetorotational instability (MRI; Balbus & Hawley, 1991). However, in some parts of the disc, the ionization degree can be insufficient to couple the magnetic field to the gas and the MRI decays there. Such region is referred to as a *dead zone*, contrary to the socalled *active parts* where the MRI operates.

The most important ionization agents are a) collisional ionization (in the inner disc region with high temperature); and b) cosmic rays and X-rays emitted by the central star (which ionize the surface layers of the disc). It leads to the disc structure suggested by the figure: IAR - inner active region, LAR - layered accretion region consisting of the dead zone (DZ) and two active surface layers (ASL), and OAR - outer active region. In this work we consider that the material with temperature above 1000 K and the surface layers of 100 g cm^{-2} (stopping depth of the cosmic rays) are active.

The ring instability

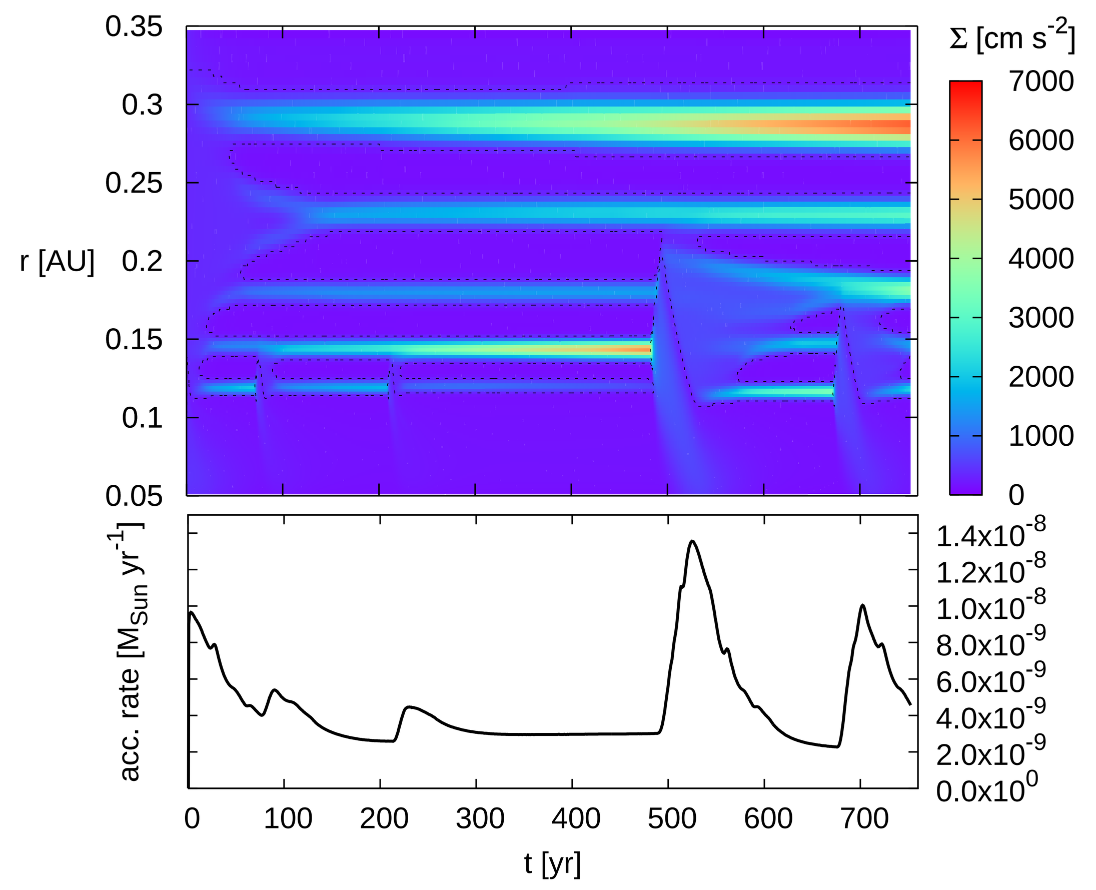
The fact that the surface density of the accreting layer is fixed externally (by the cosmic rays stopping depth) may lead to the accretion rate being a growing function of radius. In such a case the overflowing mass accumulates in the dead zone. In our simulations we found that the process of the mass accumulation can be unstable leading to a growth of the ring-like perturbations. The dead zone may eventually split into rings as shown by the figure below.





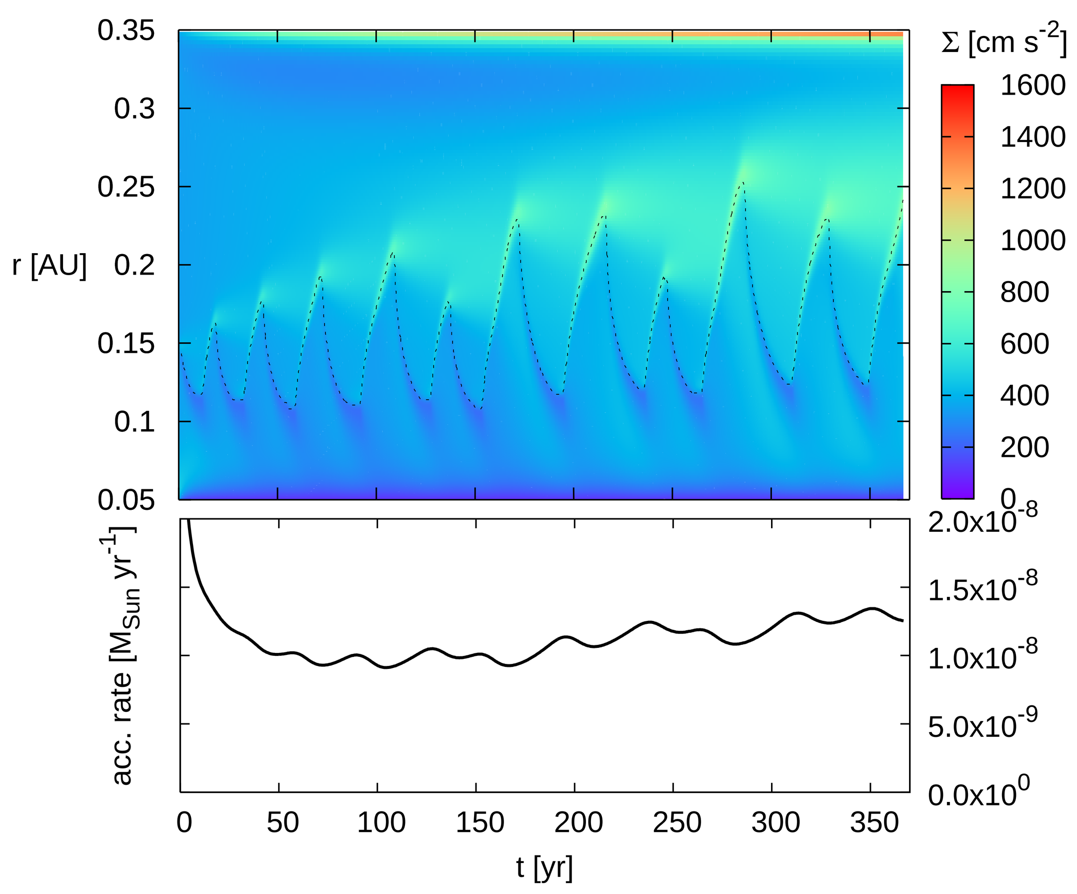
Mechanism of the instability: assume a ring-like perturbation of the disc surface density. The vertical gravitational force is higher at larger distance from the mid-plane, therefore, the thickness of the active layer H_a is smaller at the ring. The viscosity (given by the common Shakura-Sunayev prescription) is proportional to H_a, and therefore, a dip in the viscosity occurs at the ring. Since the accretion rate is proportional to the derivative of ν, it is lower at the inner edge of the ring. It works as a bottleneck in the accretion flow and the mass accumulates in the ring.

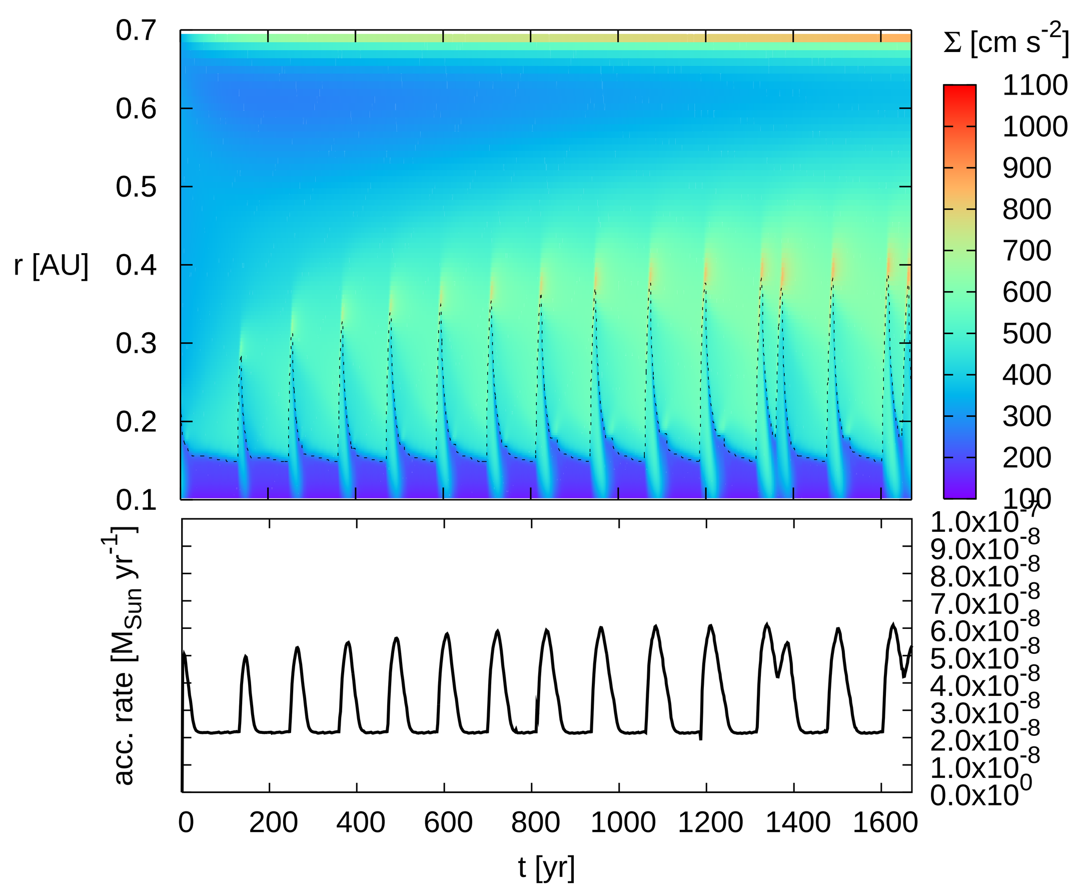
The top figure shows the evolution of the surface density in the model with $\alpha_{DZ} = 0$. We see that the dead zone quickly splits into rings. These rings may eventually be ignited (made active) and its mass accreted. At $t \doteq 500$ yr we even observe an induced ignition – the heat produced in the ignited ring is transported by the radiation to the neighbour rings and they are made active too. The bottom figure shows the accretion rate at the inner boundary of the disc $\dot{M}_{IB}$, which may increase by factor of several during the ring ignition.

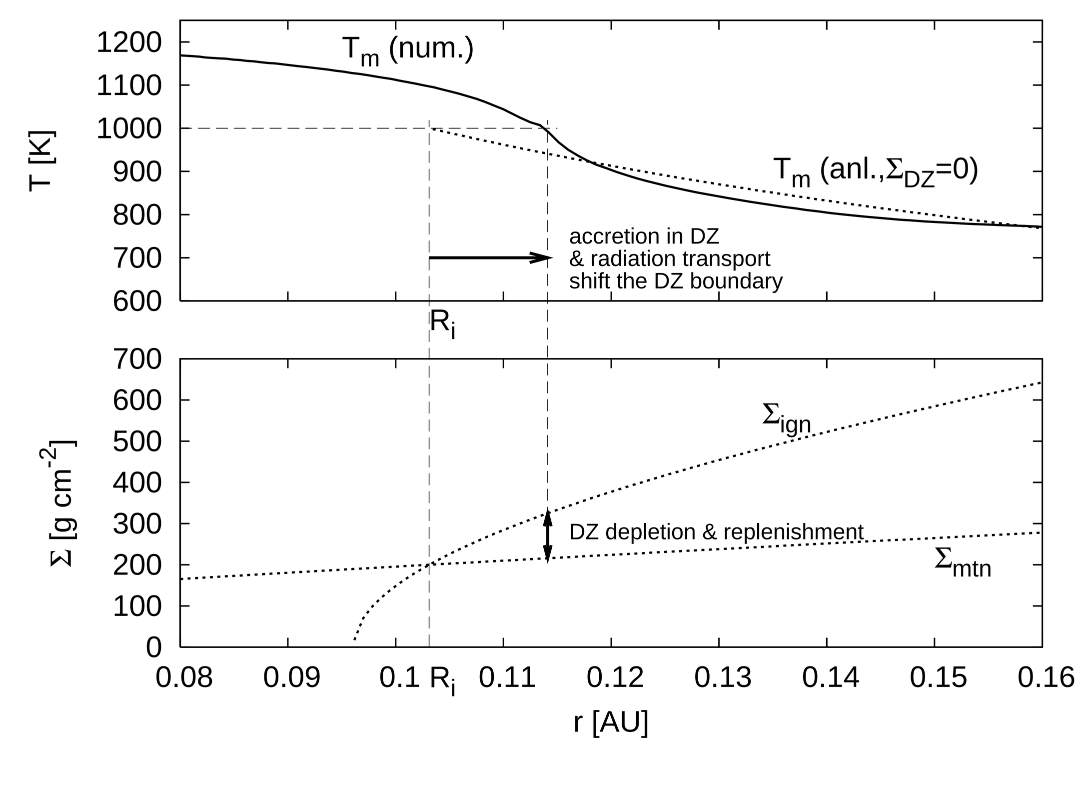


Oscillations of the inner boundary of the dead zone

Recently, there are indications that the dead zone may be not entirely dead in the sense that a residual viscosity can be maintained there by a purely hydrodynamic turbulence, excited by the non-axisymmetric waves propagating from the MRI-turbulent active layers (Flemming & Stone, 2003). Therefore, we also ran a set of models with $\alpha_{DZ} \neq 0$ (specifically, $\alpha_{DZ} = 0.1\alpha_a$ in the following two simulations). The viscosity in the dead zone suppresses the ring instability and the dead zone remains compact. On the other hand, the inner boundary of the dead zone is periodically ignited in an outburst like events, which may lead to the change of the accretion rate at the inner boundary of the disc. Left: $\alpha_a = 0.01$, the duration of the outbursts is comparable to their period, $\dot{M}_{IB}$ varies by several tenth of percent. Right: $\alpha_a = 0.02$, short regular mini-outbursts, $\dot{M}_{IB}$ changes by factor of several.







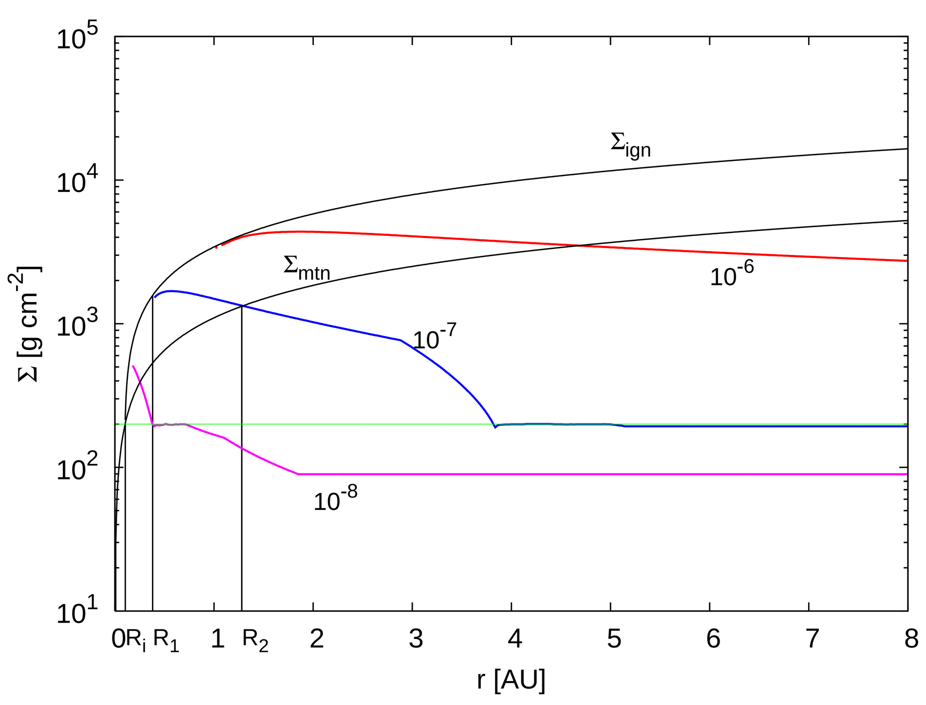
Mechanism of the dead zone ignitions: the dead zone is ignited if its temperature exceeds 1000 K. It happens if the surface density of the layered region (which grows due to mass accumulation) exceeds Σ_{ign}. The accretion rate in the ignited region increases, and the surface density starts to drop. At Σ_{mtn}, the temperature of the ignited region drops below 1000 K and the layered structure is reestablished.

Stationary states with $\alpha_{DZ} \neq 0$

If there is a residual viscosity in the dead zone, the mass accumulation can be compensated by the accretion in the dead zone and stationary states may exist. We search for these stationary states solving equation:

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

using 1D numerical code similar to the one used by Armitage et al. (2001) and Stępiński (1999). The next figure shows the stationary surface density profiles for different accretion rates at the outer boundary. The part of the dead zone with surface density above Σ_{mtn} may still be ignited by some external event, and this mass (which may be as high as 0.01 M$_\odot$ for $\dot{M}_{OB} = 10^{-6}$ M$_\odot$ yr^{-1}) can serve as a reservoir for the FU Orionis type outburst.



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