CHELYABINSK STATE UNIVERSITY CSU

Ural Federal University named after the first President of Russia B.N.Yeltsin

RSF Russian Science Foundation

Physical and chemical vertical structure of the magnetostatic accretion disks of young stars

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   - Observations of the magnetic fields in the ADs
   - MHD model of the ADs
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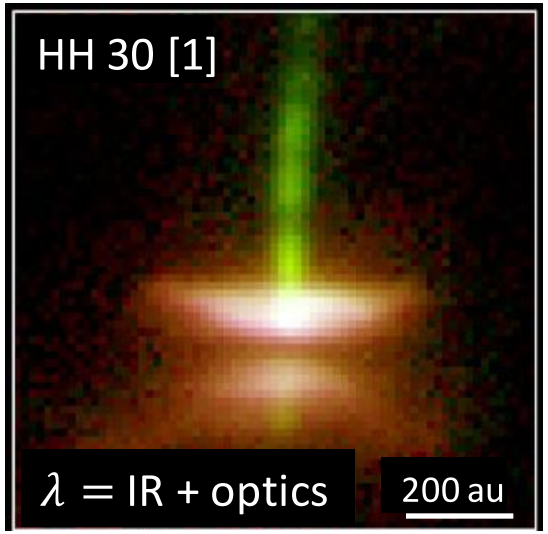
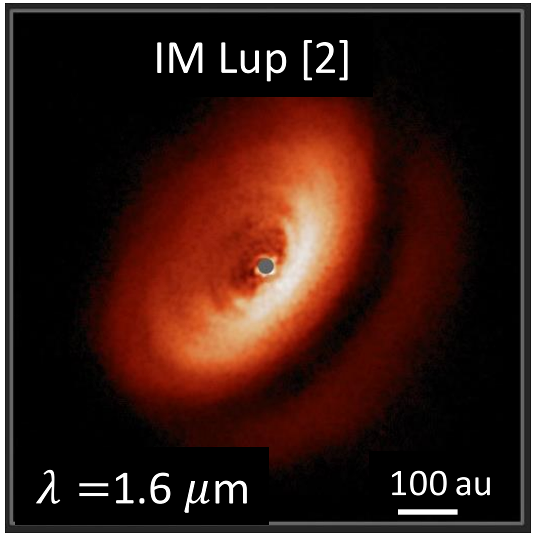
3. Simulation results
   - Magnetic field, density and temperature
   - Chemical structure
4. Conclusion

Accretion disks of young stars (ADYS)





Characteristics:

- Sizes: $R = 100 - 1000$ a.e.
- Geometrically thin, $H \ll R$, optically thick
- Masses: 0.001-0.1 $M_{\odot}$
- Temperatures: 10-1000 K

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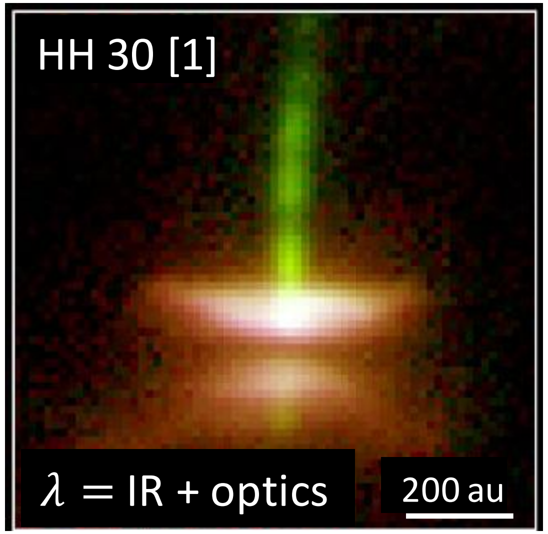

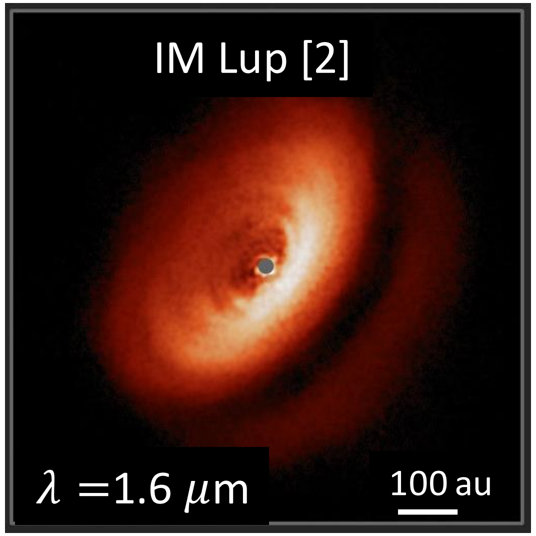

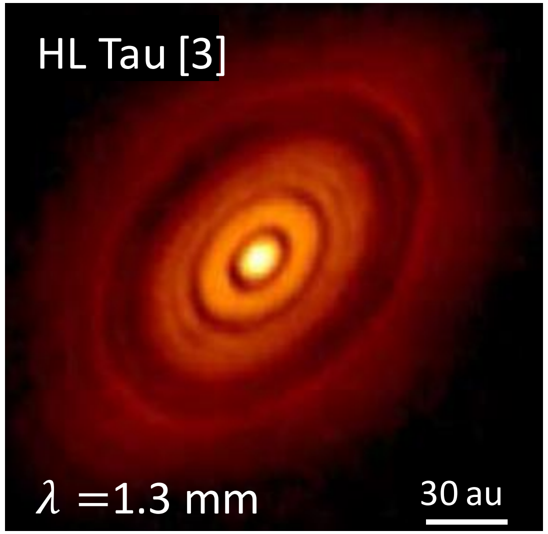

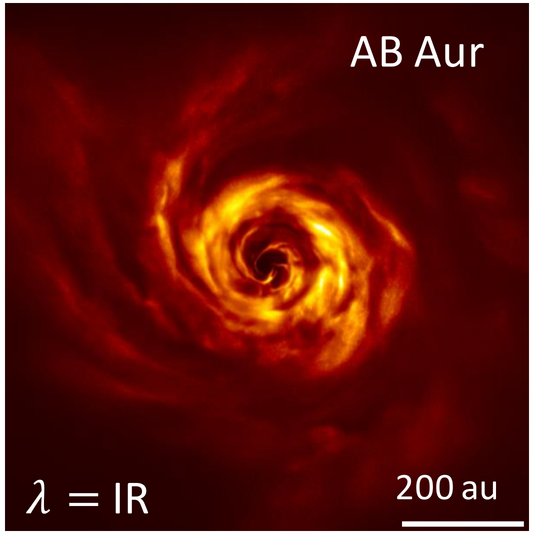

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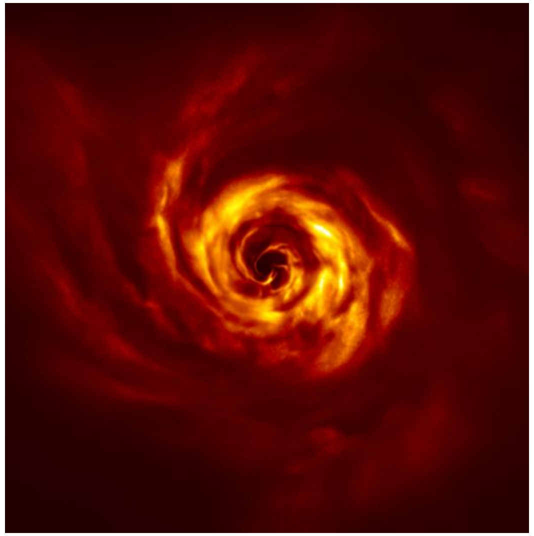
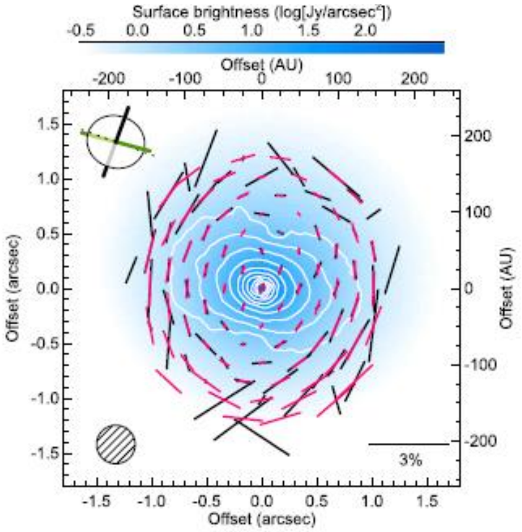
→ protoplanetary disks (PPD)

Magnetic field in the ADYS

POLARIZATION MAPPING

→ GEOMETRY OF THE MAGNETIC FIELD

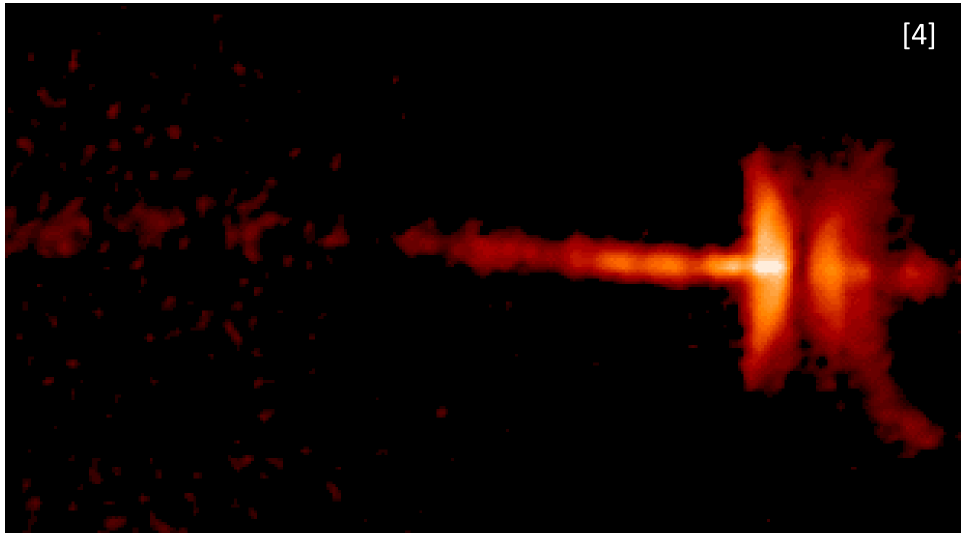




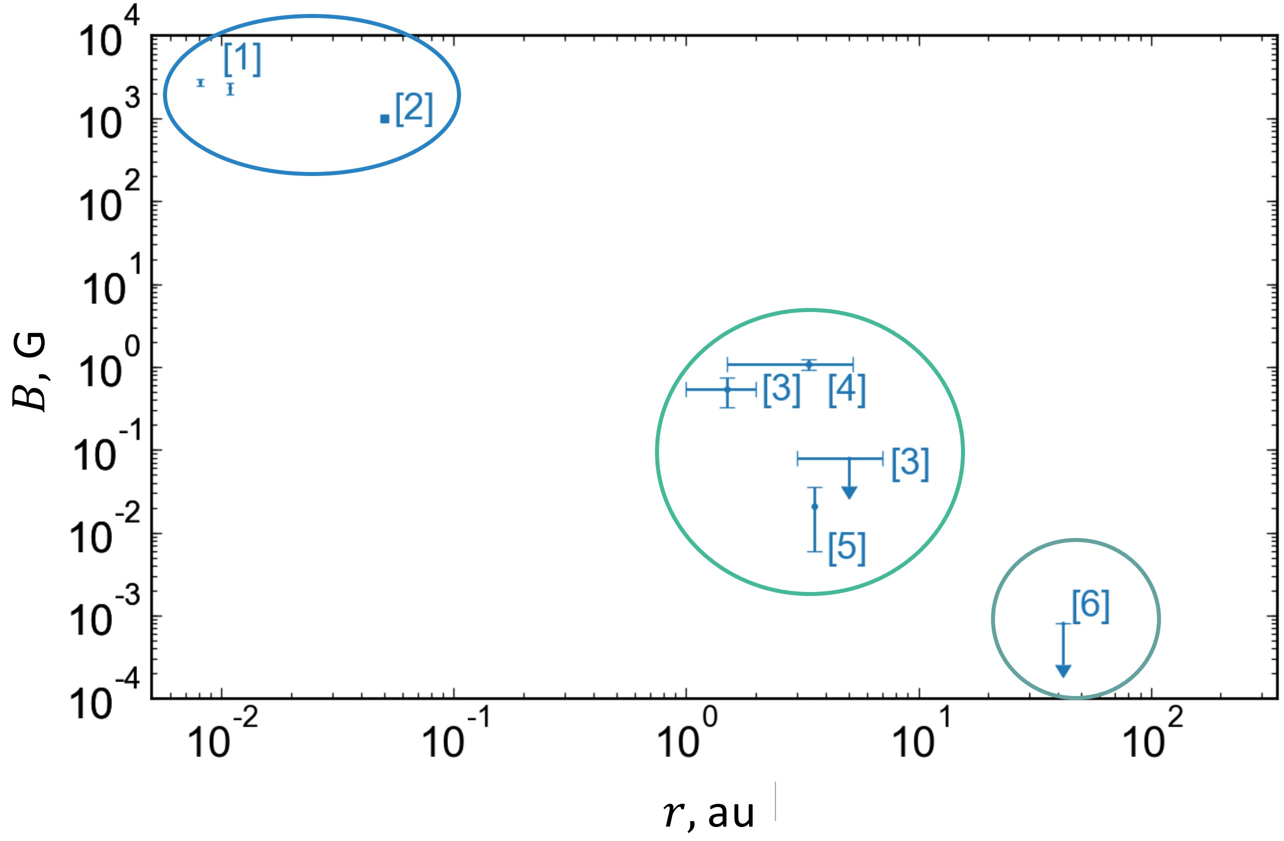
Boccaletti et al., 2020, A&A, 637, L5   Li, et al, 2016, ApJ, 832, 18

OUTFLOWS AND JETS IN THE ADYS

→ INDIRECT SIGNS



Measurements of the magnetic field strength



Zeeman broadening (optical range)

[1] Yang & Johns-Krull, 2011, ApJ, 729, 83

[2] Donati, et al., 2005, Nature, 438, 466

Remnant magnetization of meteorites

[3] Fu et al., 2020, JGRE, 125, e06260

[4] Butler, 1972, E&PSL, 17, 120

[5] Cournede et al., 2015, E&PSL, 410, 62

Zeeman splitting of CN (submm/mm range)

[6] Vlemmings et al., 2019, A&A, 24, L7

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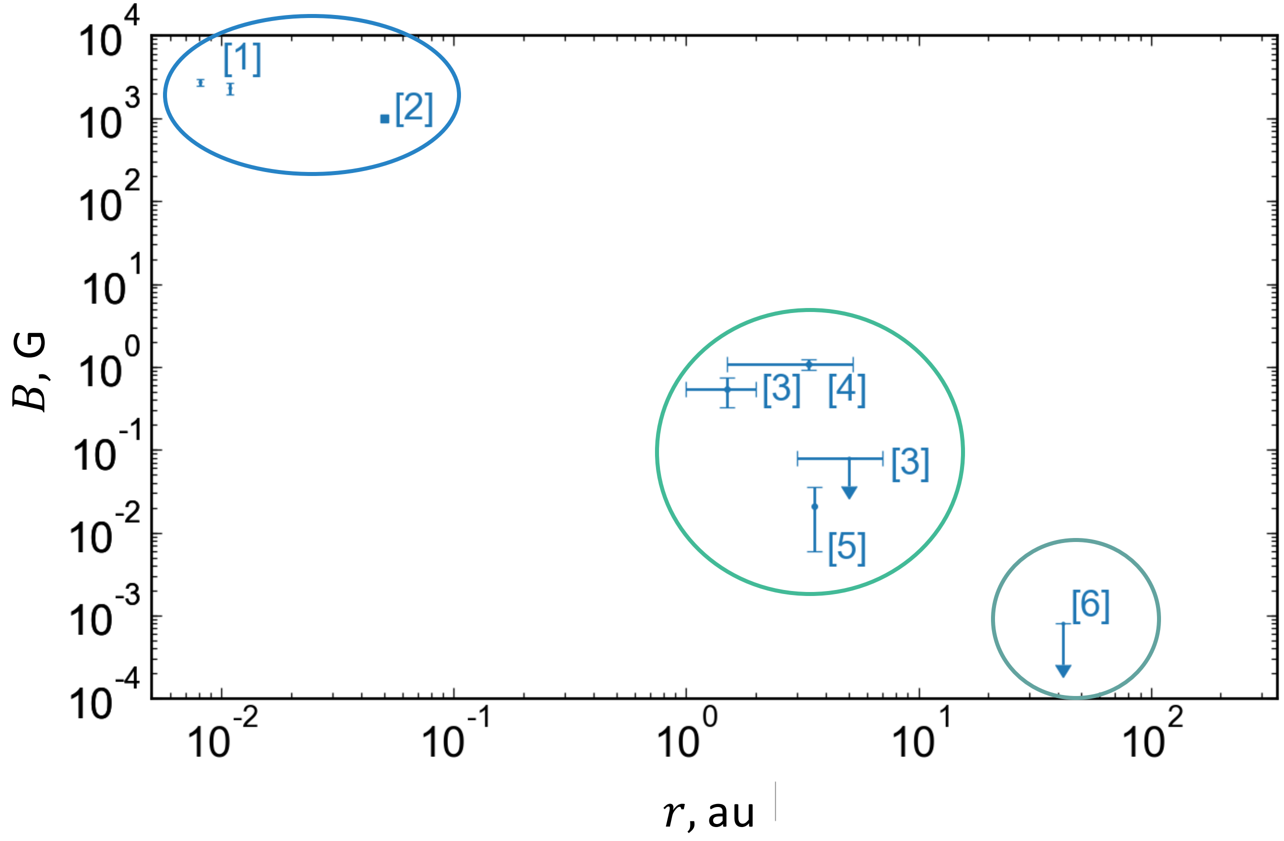

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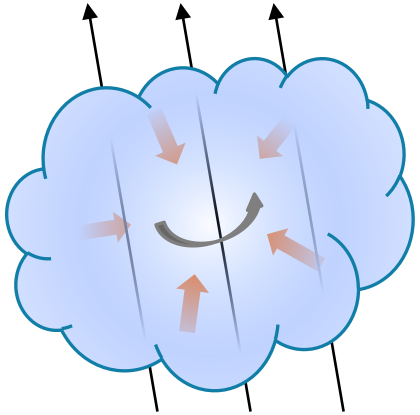
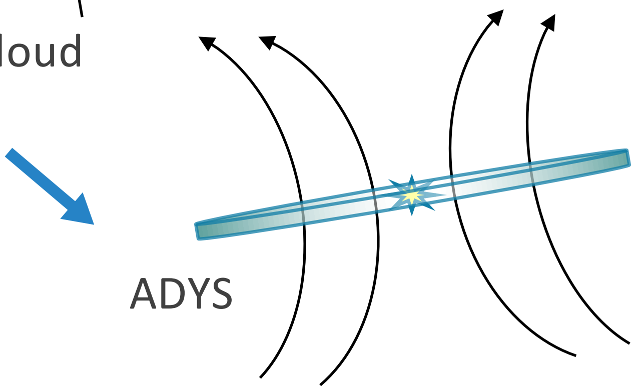
MHD model of the ADYS

FOSSIL NATURE OF THE MAGNETIC FIELD



Protostellar cloud



ADYS

MODEL OF DUDOROV AND KHAIBRAKHMANOV

- **Radial structure of the disk**: Shakura and Sunyaev equations (Shakura, Sunyaev, 1973, A&A, 24, 337)
- **Vertical structure**: hydrostatic equilibrium
- **Ionization fraction**: e-, m+, dust grains g, cosmic rays, X-rays, radioactive decay, thermal ionization, dust grains evaporation
- **Magnetic field**: induction, Ohmic and magnetic ambipolar diffusion, magnetic buoyancy, the Hall effect

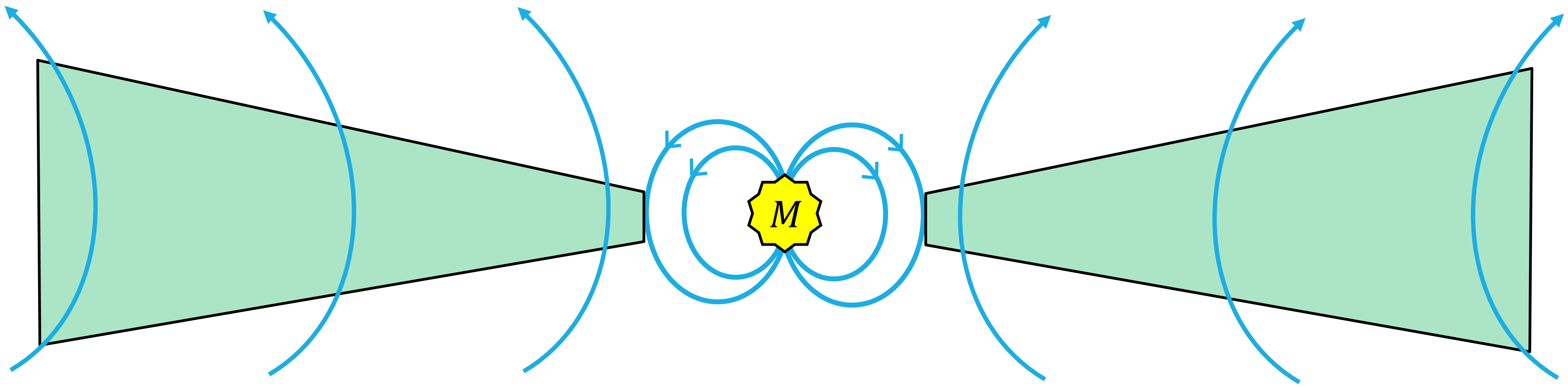
Dudorov, Khaibrakhmanov, 2014, Ap&SS, 352, 103

Khaibrakhmanov et al., 2017, MNRAS, 464, 586

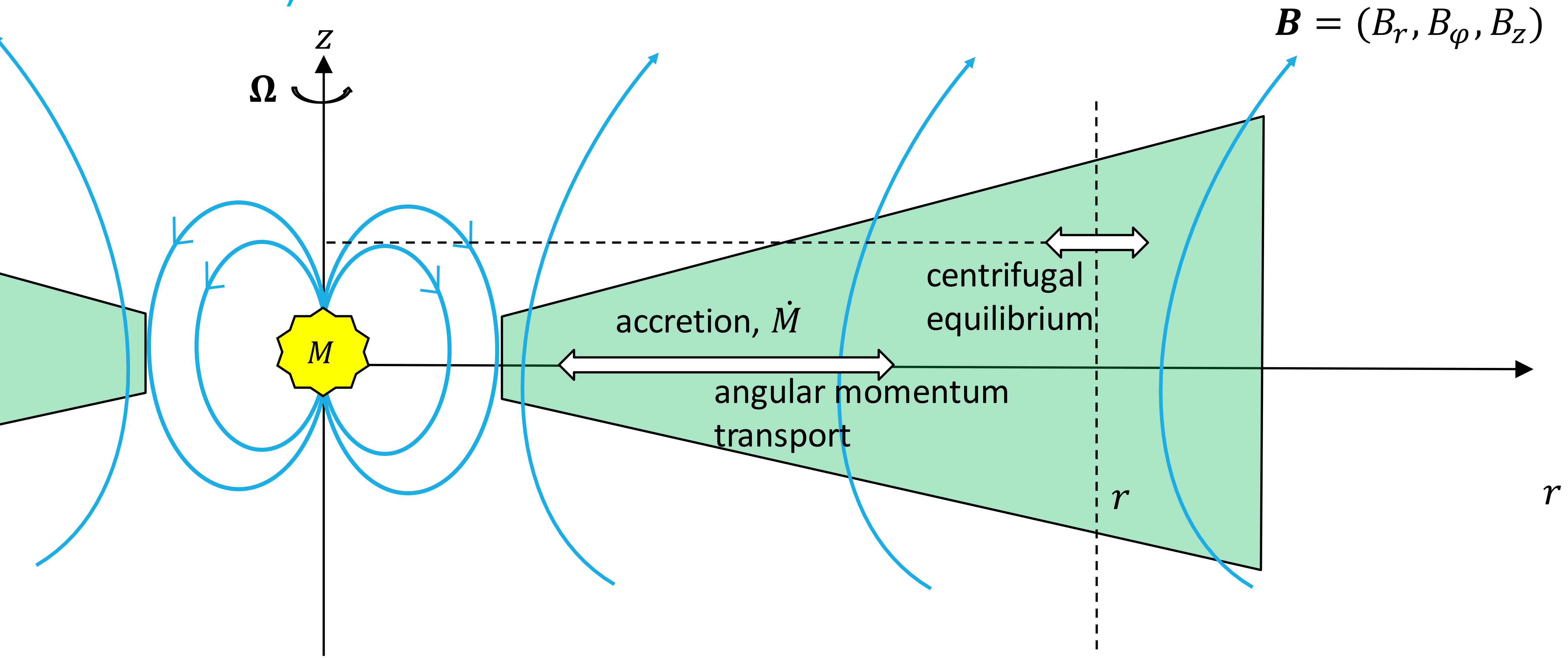
Aim: Investigation of the dynamics of the ADYS with fossil large-scale magnetic field

Tasks:

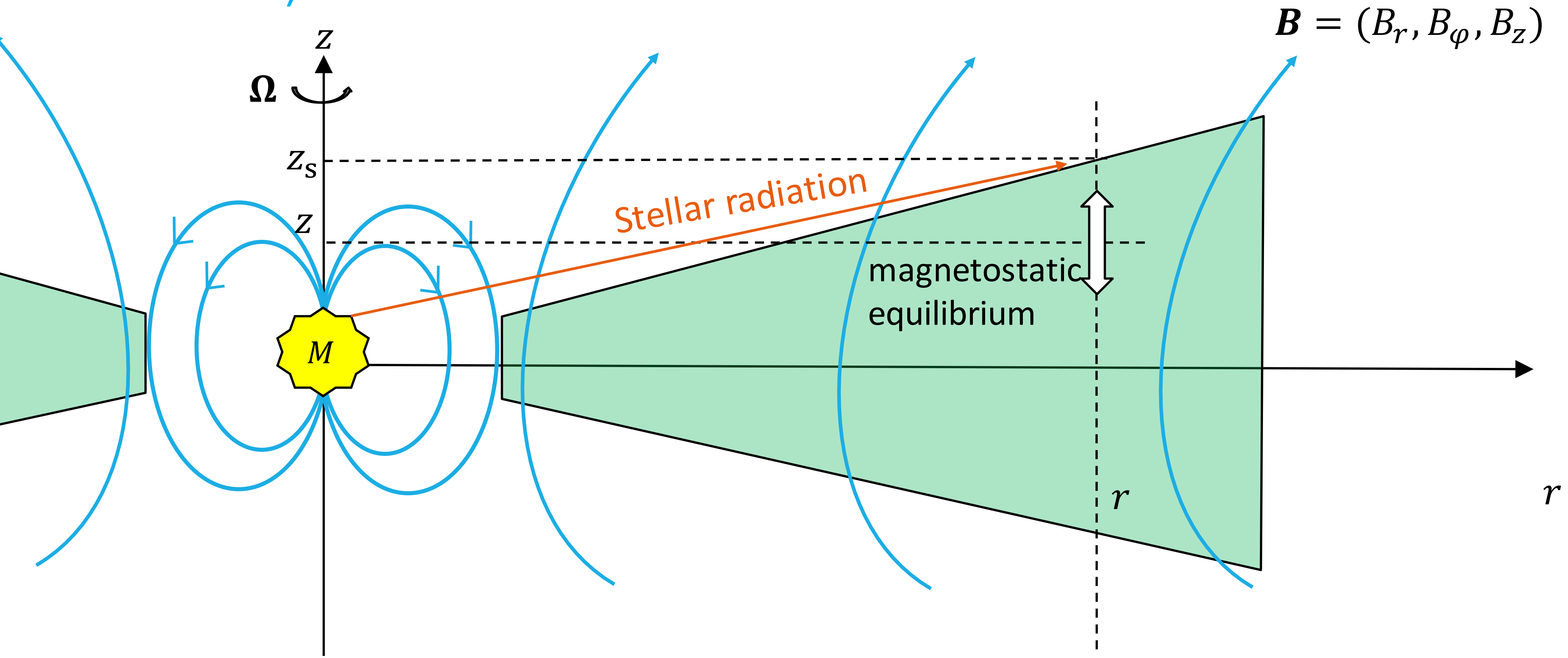
- Solution of the equations of the magnetostatic equilibrium of the ADYS
- Modelling of the chemical structure of the AD. Analysis of spatial distribution of CN molecules



Problem statement:
a) radial structure of the disk



Problem statement:
a) vertical structure of the disk



Main equations

MHD equations: gravitation, viscosity (→ turbulence), magnetic field, radiative conductivity, magnetic field diffusion

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \mathrm{div}\,(\rho \vec{v}) = 0 & (1) \\ \rho \dfrac{d\vec{v}}{dt} = -\nabla\left(p + \dfrac{B^2}{8\pi}\right) + \rho\vec{g} + \mathrm{div}\sigma' + \dfrac{1}{4\pi}(\vec{B}\nabla)\vec{B} & (2) \\ \rho T \dfrac{ds}{dt} = \sigma_{ik}{}' \dfrac{\partial v_i}{\partial x_k} + \mathrm{div}\,\vec{F} & (3) \\ \dfrac{\partial \vec{B}}{\partial t} = \mathrm{rot}\left[\vec{v}\,, \vec{B}\right] + \eta \nabla^2 \vec{B} & (4) \end{cases}$$

σ_{ik} - viscous stress tensor, $\vec{F}$- radiation energy flux density, η – magnetic diffusivity. We use equation of state of the ideal gas.

Equations of the vertical structure

(2) → $$\frac{dp}{dz} = -\rho \frac{GM}{r^3} z - \frac{d}{dz}\left(\frac{B_\varphi^2}{8\pi}\right)$$ equation of magnetostatic equilibrium

(3) → $$\frac{16\sigma T^3}{3\kappa_R \rho} \frac{dT}{dz} = -F_z$$ radiative energy flux density

(3) → $$\frac{dF_z}{dz} = \frac{3}{2} \alpha p \Omega_k$$ equation of thermal balance

(4) → $$\frac{d^2 B_\varphi}{dz^2} = -\frac{3}{2} \frac{B_z}{\eta} v_k \frac{z}{r^2}$$ induction equation (advection-diffusion balance)

Unknown variables:

p, T, F_z, B_φ

Coefficients:

$\kappa_R(\rho, T),\ v_k = r\Omega_k, B_z, T_{eff}$

Khaibrakhmanov, Dudorov, 2021, CPMJ, 6(1), 53-78

Boundary conditions

Midplane, $z = 0$:

$$\begin{cases} F_z = 0 & \text{by definition} \\ B_\varphi = 0 & \text{equatorial symmetry} \end{cases}$$

Photosphere, $z = z_s$:

$$\begin{cases} p = p_s, & \\ T = T_{eff}, & \\ F_z = \sigma T_{eff}^4 & \text{thermal balance} \\ B_\varphi = B_{ext}, & \text{match to the external solution} \end{cases}$$

(e.g., Uchida-Shibata outflow: $B_\varphi > B_z$, $\beta \sim 1$)

two-point boundary value problem

Disk atmosphere ($\tau_R < 1$):

- Constant temperature determined by stellar irradiation

$$\sigma T_{irr}^4 = f \frac{L_\star}{4\pi r^2}, f = 0.05$$

- Hydrostatic density profile

Model parameters

- T Tauri star with typical parameters: $M = 1M_{\odot}, \dot{M} = 10^{-8}\, M_{\odot}/\mathrm{yr}, \alpha = 0.01$
- Opacity $\kappa_R(\rho, T)$ – interpolation of the tables of Semenov et al. (2003, A&A, 410, 611) and OPAL (Iglesias, Rogers, 1996, ApJ, 464, 943)
- Simulations of the vertical structure are performed for $r = 0.25, 1, 10, 50$ au
- Boundary values:
  - $p_s = n_{ext} k T_{ext}$
  - $B_{ext} = 8\pi p_s/\beta$, where β – free parameter.

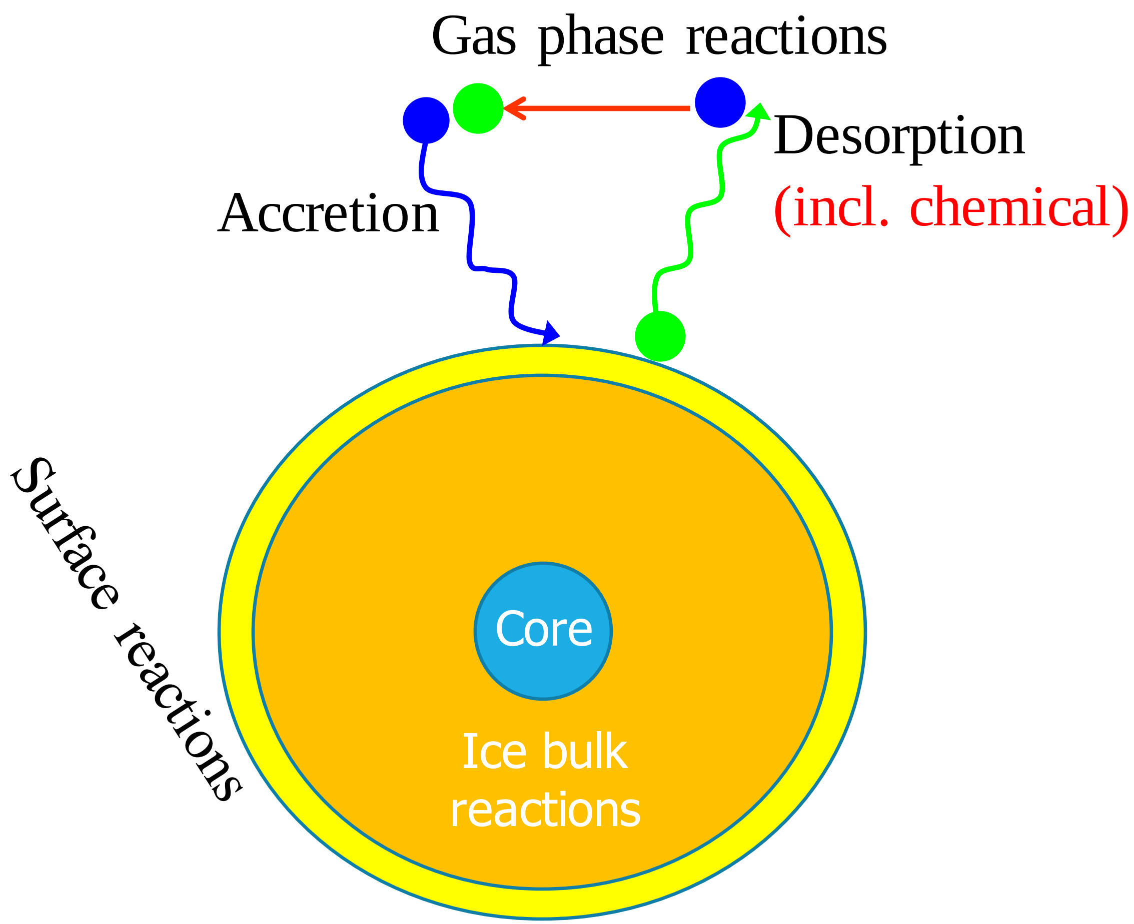
Method of solution

- Equation for B_φ - ODE of the 2nd order. Analytical solution

$$B_\varphi(r,z) = B_{ext}\frac{z}{z_s} + \frac{1}{4}\frac{v_k z}{\eta}B_z\left[\left(\frac{z}{r}\right)^2 - \left(\frac{z_s}{r}\right)^2\right]$$

- Equations for (P, F_z, T) - ODEs system of the 1st order. It is solved with the Runge-Kutta scheme of the 4th order with automatic step size control for relative accuracy 10^{-4}
- The coordinate of the photosphere z_s is determined by the shooting method

Chemical modelling – MONACO



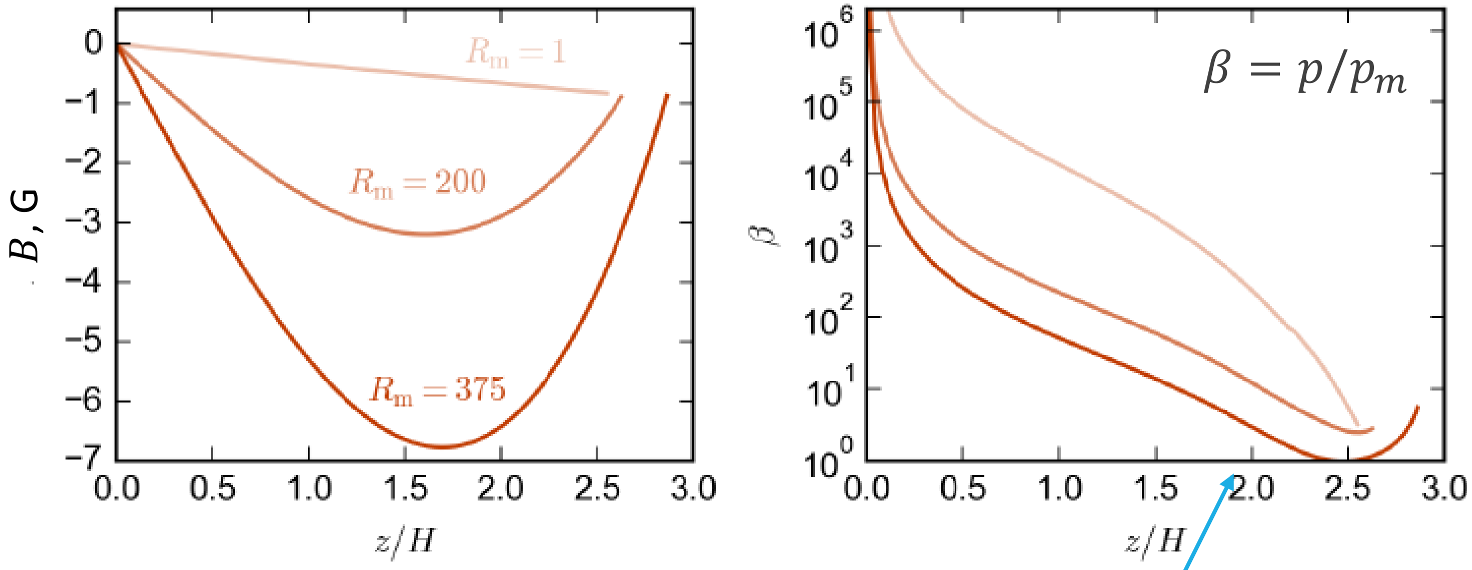
⇒ Coupled system of the ODEs of the chemical kinetics

Online version:
https://astro.ins.urfu.ru/monaco

Vasyunin, Herbst, 2013, ApJ, 762, 86
Vasyunin, et al., 2017, ApJ, 842, 33

Vertical structure. Magnetic field

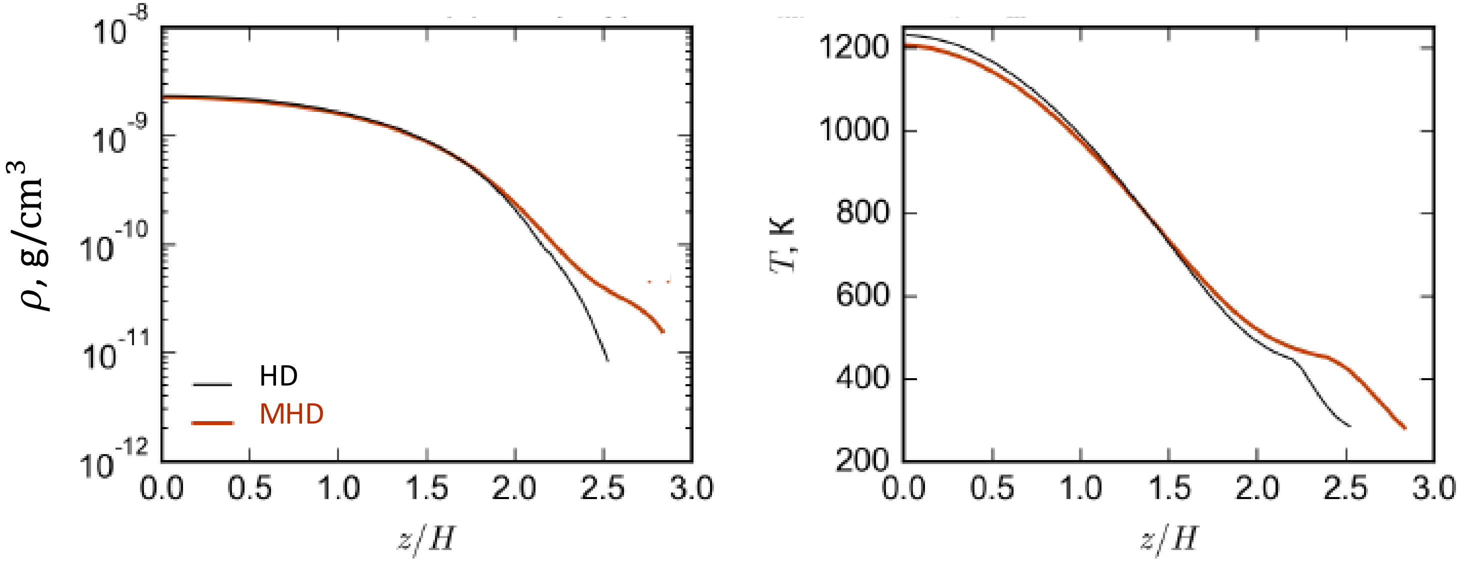
Simulation results for $r = 0.2$ au, $B_{ext} = -0.1B_z$



- For $R_m \equiv v_k H/\eta > 1$ the profile $B_\varphi\,(z)$ is non-monotonic.
- Dynamically strong magnetic field, $\beta \sim 1$, is generated near the surface for $R_m \gg 1$

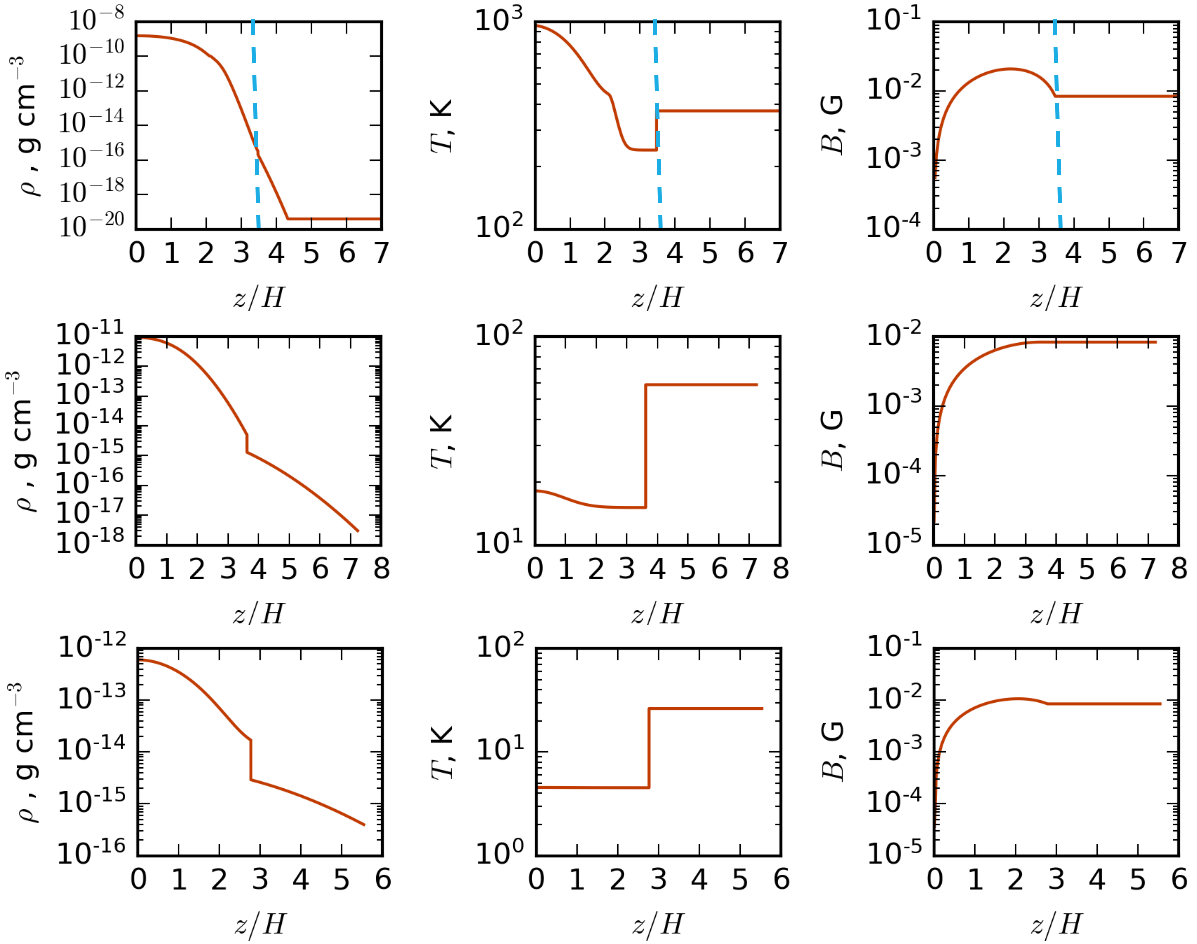
Vertical structure. Density and temperature

Simulation results for $r = 0.2$ au, $B_{ext} = -0.1 B_z$



- Expansion of the disk near the surface due to magnetic pressure

Vertical structure at different radii

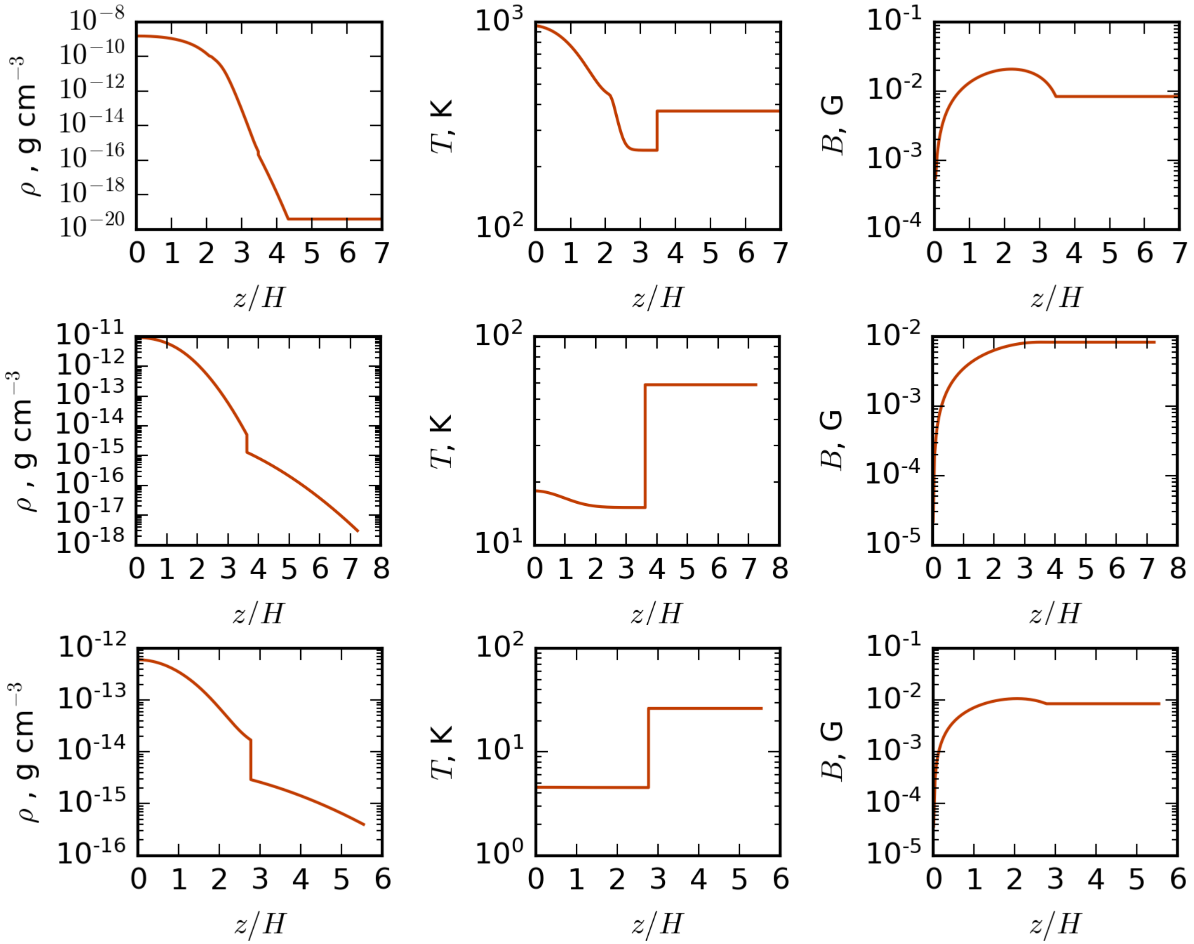


$r = 0.25$ au

$r = 10$ au → MONACO

$r = 50$ au

Vertical structure at different radii

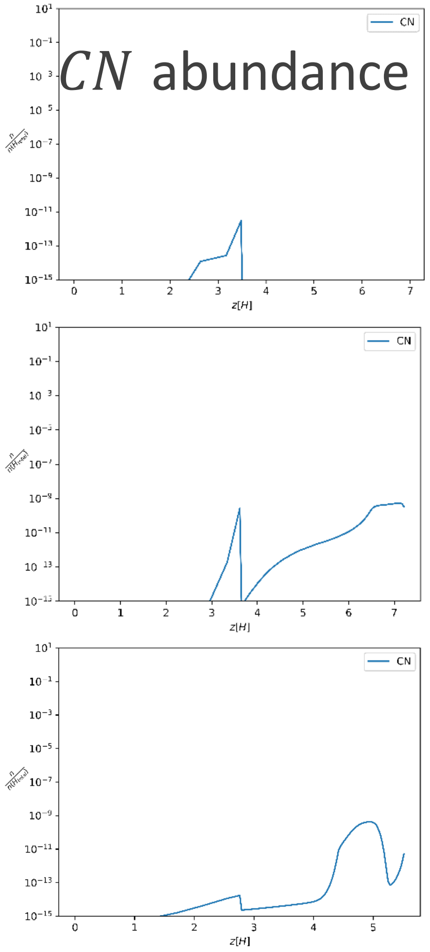


$r = 0.25$ au

$r = 10$ au

$r = 50$ au

CN abundance



Conclusion

- Inside the "dead" zone, $r = 0.2 - 30$ au, magnetic field does not influence the vertical structure of the disk. Outside the "dead" zone, magnetic pressure gradient can cause either expansion, or compression of the disk depending on the surface conditions (Khaibrakhmanov, Dudorov, 2021, CPMJ, 6(1), 53-78).
- Chemical modelling shows that the CN is potentially observable at $r \geq 10$ au. The abundance of CN agrees in general with observations (Cazoletti et al., 2018, A&A, 609, A93). The CN emission can be used to measure the magnetic field strength at the disk photosphere and above it. Full 2D modelling is required to make accurate predictions for future observations.

Thanks for attention!

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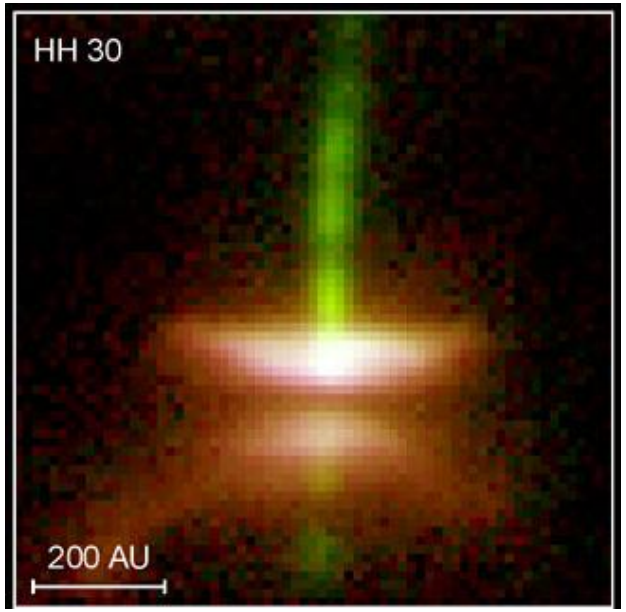

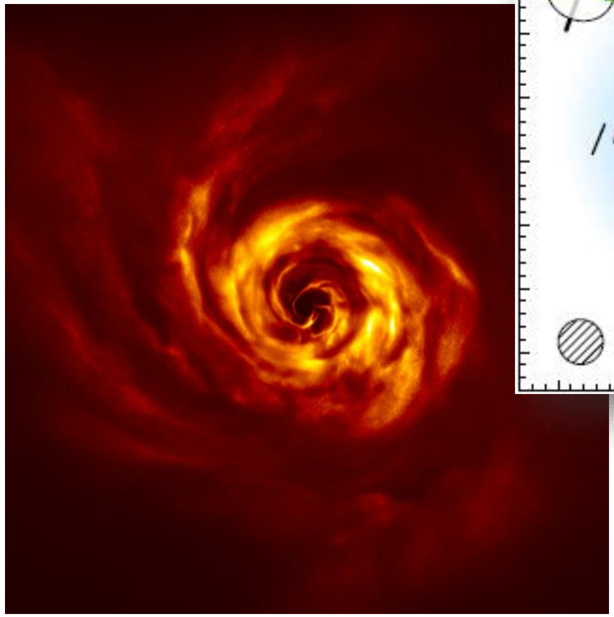

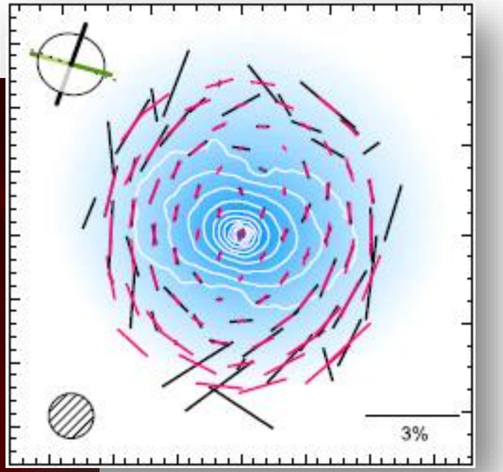

Credits

[1]: Chris Burrows (STScI), the WFPC2 Science Team and NASA

[2]: ESO/H. Avenhaus et al./DARTT-S collaboration

[3]: ALMA (ESO/NAOJ/NRAO)

[4]: NASA, A. Watson (UNAM), K. Stapelfeldt (JPL), J. Krist (STScI) and C. Burrows (ESA/STScI)