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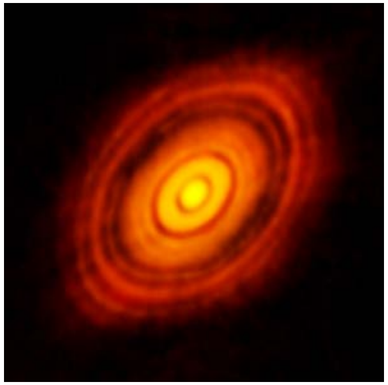

FORMATION AND EVOLUTION OF PROTOSTELLAR DISKS

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Outline

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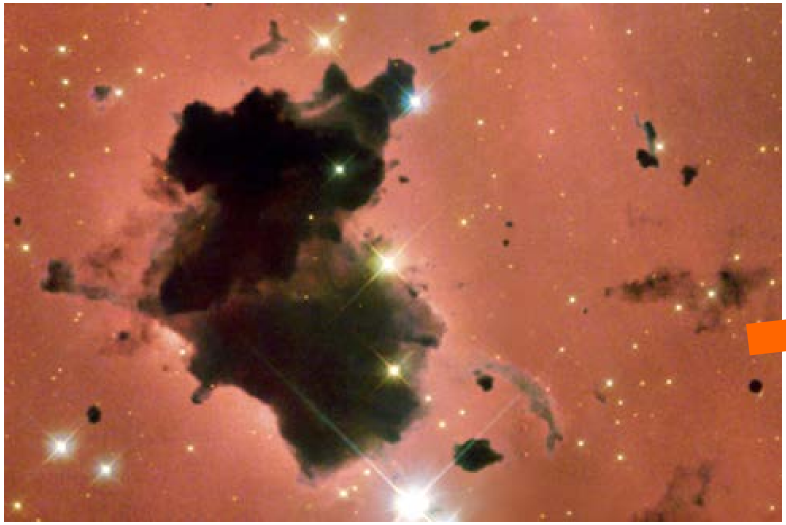
Contemporary star formation

MOLECULAR CLOUD CORE (PROTOSTELLAR CLOUD)

STAR WITH PROTOPLANETARY DISK



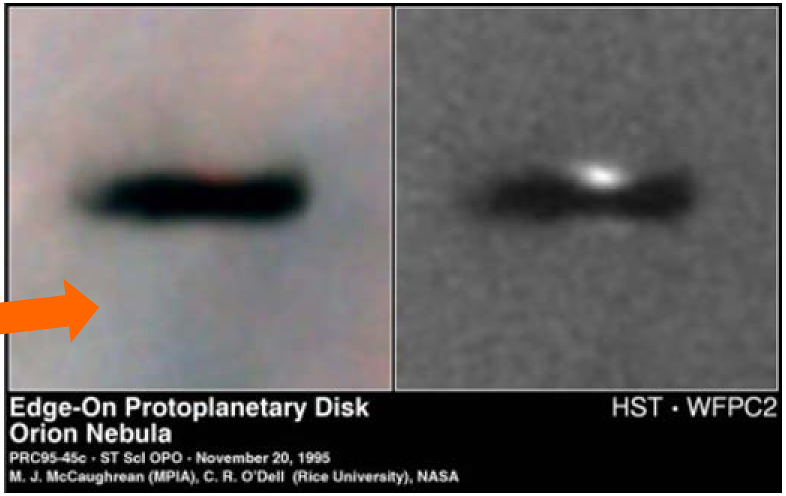
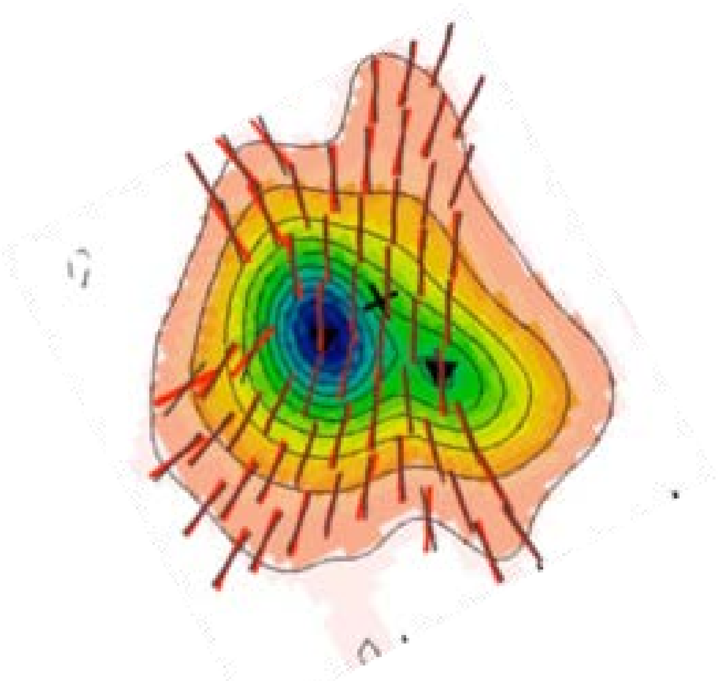


Photo: Hubble Heritage Team (STScI/AURA), NASA

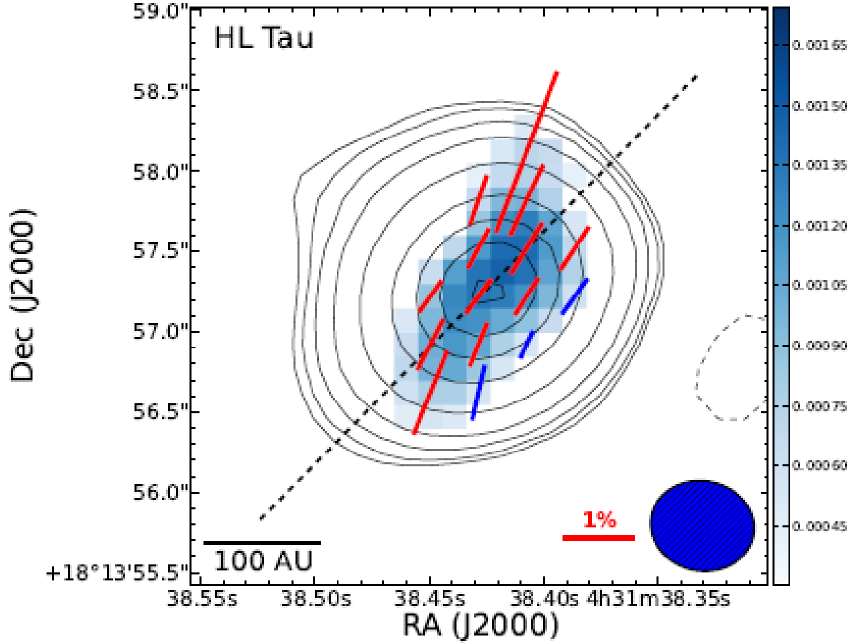
Magnetic field of young stellar objects (YSO)

MOLECULAR CLOUD CORE NGC 1333 IRAS 4A[1]



[1]Girart et al., 2006, Sci, 313, 812

PROTOPLANETARY DISK HL TAU[2]



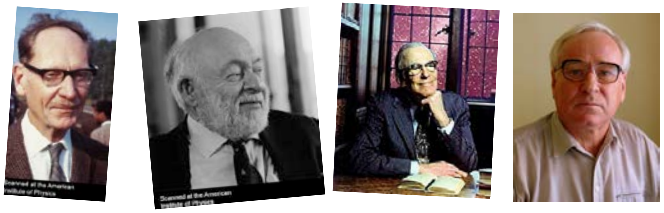
[2]Stephens et al., 2014, Nat, 514, 597

Magnetic field of YSO

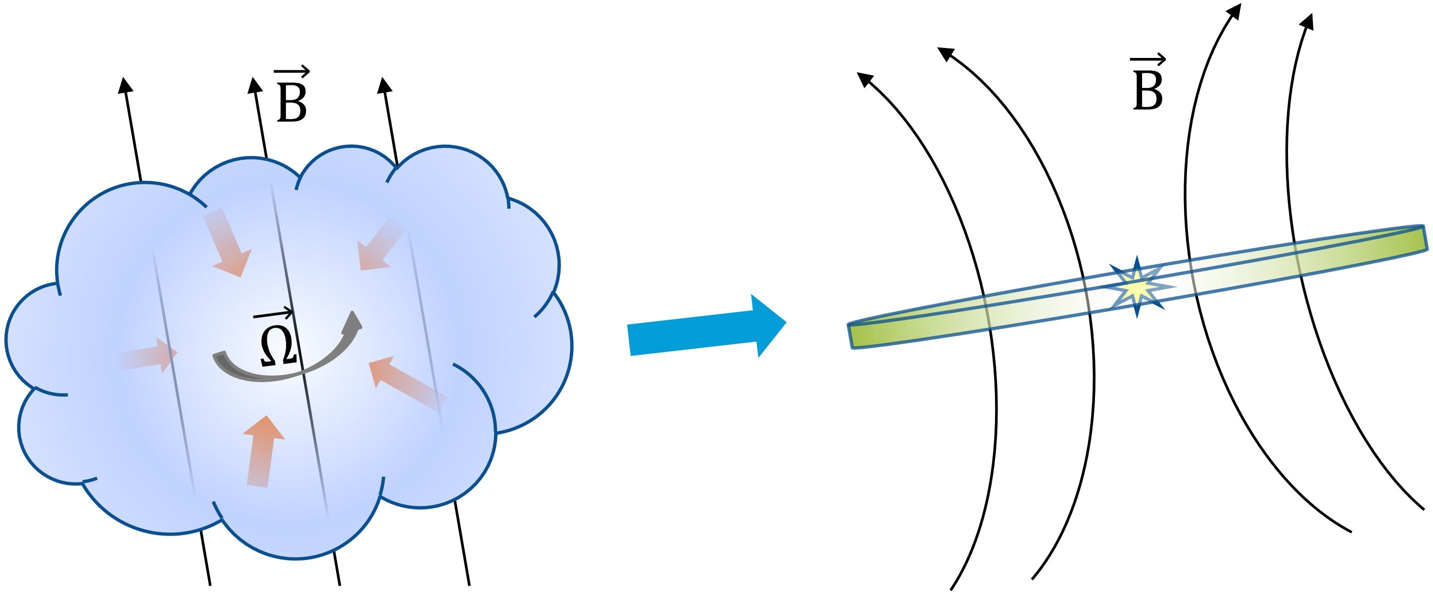
∃!

Objects	B, Gs	method	Reference
Protostellar clouds	$10^{-4} - 10^{-5}$	Zeeman	Crutcher et al., 2004, ApJ, 600, 279
Accretion disk FU Ori	10^3	Zeeman	Donati et al., 2005, Nat, 438, 466
T Tauri stars	$1000 - 3000$	Zeeman	Yang & Johns-Krull, 2011, ApJ, 729, 83
Protosolar nebula	$0.1 - 1$	Remnant magnetization	Levy, 1978, Nat, 26, 481

Theory of fossil magnetic field



- The magnetic flux, $\int \vec{B} d\vec{s}$, of protostellar clouds is partially conserved during star formation
- The magnetic field of young stars with accretion disks is fossil one[1,2]



[1] Dudorov, 1995, ARep, 39, 790

[2] Dudorov, Khaibrakhmanov, 2015, AdSpRes, 55, 843

Basic equations

MHD with Ohmic diffusion and magnetic ambipolar diffusion

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \tag{1}$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\frac{1}{\rho}\nabla P + \frac{1}{4\pi\rho}\left[\mathrm{rot}\,\vec{B} \times \vec{B}\right] - \nabla\Phi, \tag{2}$$

$$\frac{\partial \vec{B}}{\partial t} = \mathrm{rot}\left[(\vec{v} + \vec{v}_{ad}) \times \vec{B}\right] - \mathrm{rot}\left(\nu_m \mathrm{rot}\,\vec{B}\right), \tag{3}$$

$$\rho\left[\frac{\partial \varepsilon}{\partial t} + (\vec{v} \cdot \nabla)\varepsilon\right] + P\nabla \cdot \vec{v} = 0, \tag{4}$$

$$\nabla^2\Phi = 4\pi G\rho, \tag{5}$$

Equation of state: $P = (\gamma - 1)\varepsilon\rho$

Magnetic field diffusion

- Ohmic diffusion – currents dissipation

$$\nu_m = \frac{c^2}{4\pi\sigma_e}, \tag{8}$$

$$\sigma_e = \frac{e^2 n_e}{m_e \nu_{en}}, \tag{9}$$

where e and m_e are charge and mass of an electron, n_e – electrons concentration, $\nu_{en} = \langle\sigma v\rangle_{en} n_n$ – collision rate, $\langle\sigma v\rangle_{en} = 10^{-7}\ \mathrm{cm}^3/\mathrm{s}$.

- Magnetic ambipolar diffusion – the drift of plasma through the neutral gas under the action of the electromagnetic force

$$\vec{v}_{ad} = \frac{\mathrm{rot}\,\vec{B} \times \vec{B}}{4\pi R_{in}} \tag{7}$$

Ionization fraction

Ionization equation[1]

$$(1 - x_s)\xi = \alpha_r x_s^2 n + \alpha_g x_s n, \tag{6}$$

- $x_s = n_e/(n_e + n_i + n_n)$ – ionization fraction
- ξ – ionization rate
- α_r – radiative recombinations rate
- α_g – rate of recombinations on the dust grains

Ionization by cosmic rays and radionuclides is taken into account, as well as dust grains evaporation.

[1] Dudorov, Sazonov, 1987, Nauch.Inform., 63, 68 (in Russian)

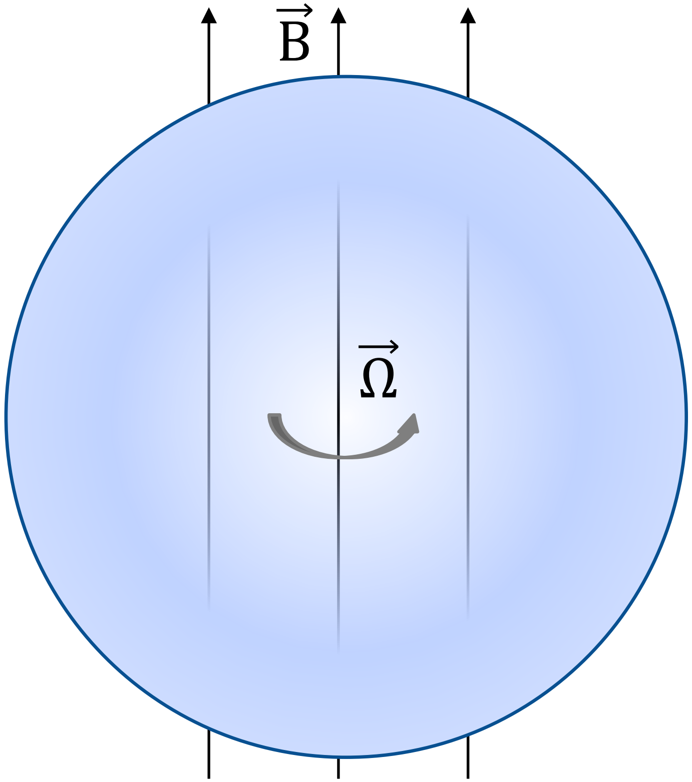
Numerical code

- *Enlil* – two-dimensional code for modelling of the axi-symmetric MHD flows[1]
- Based on the quasi-monotonic TVD-scheme of the high order. HLLD-solver is used
- Divergence cleaning – generalized Lagrange multipliers method
- Puasson's equation – alternating directions method
- Magnetic diffusion – fully implicit absolutely stable scheme[2]

[1] Dudorov, Zhilkin, Kuznetsov, 1999, Matem.Mod, 11(11), 109 (in Russian)
[2] Zhilkin, Pavlyuchenkov, Zamozdra, 2009, Astron. Rep., 53(7), 590

Problem statement and parameters

We consider uniform rotating cloud with uniform magnetic field



$n_0 = 4.1 \times 10^5 \text{ cm}^{-3}$

$M = 1\ M_\odot$

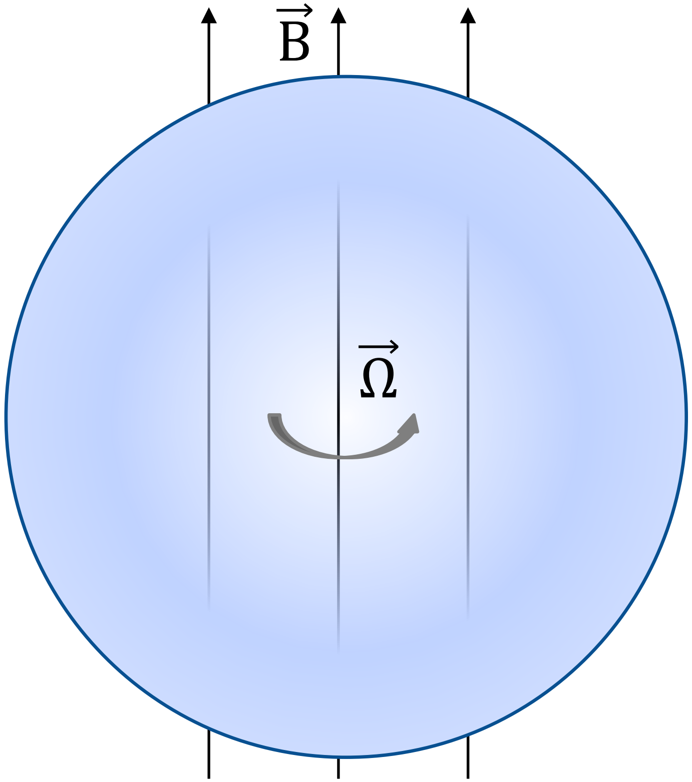
$R = 0.022$ pc

$B_0 = 1.4 \times 10^{-4}$ Gs

$\mathrm{T} = 10$ K

Problem statement and parameters

We consider uniform rotating cloud with uniform magnetic field

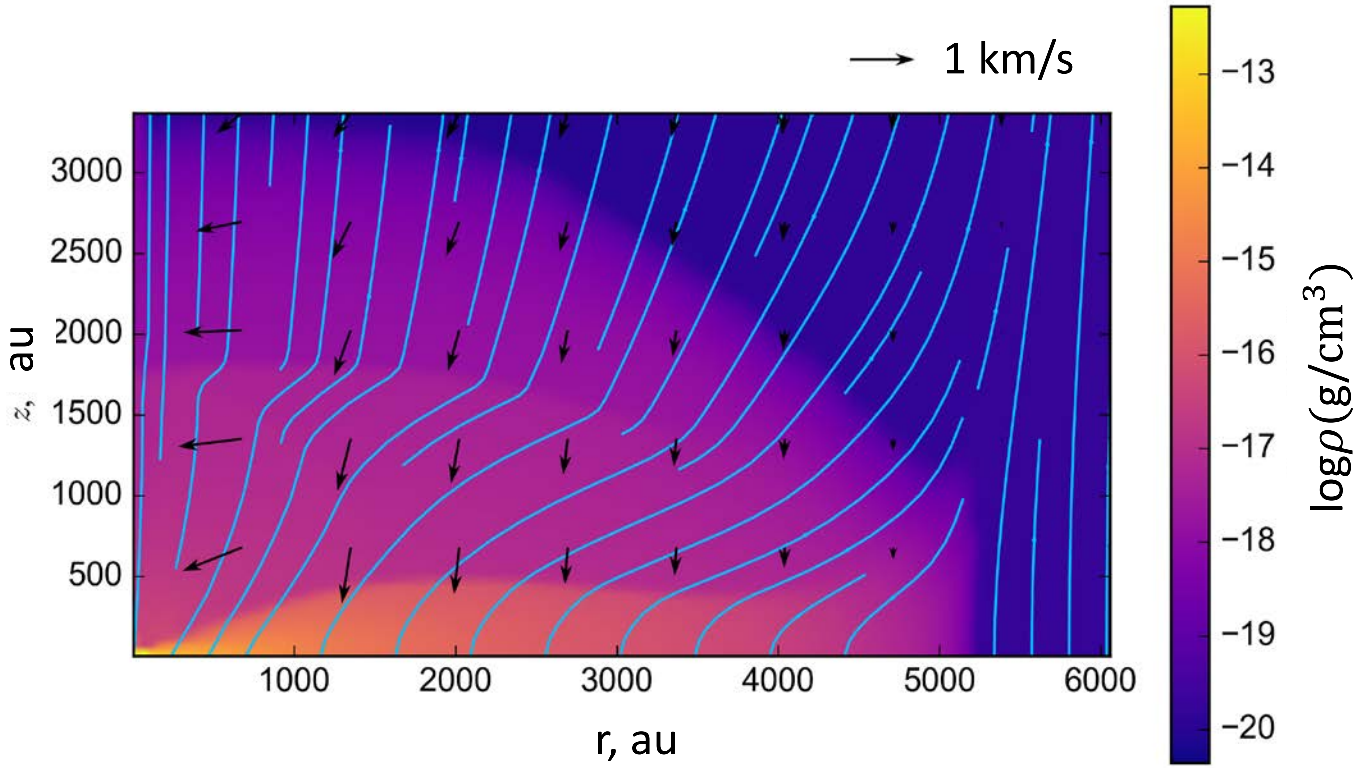


- Isothermal collapse: $\gamma = 1.001$

$$\frac{E_{th}}{E_G} = 0.3 \quad \frac{E_\Omega}{E_G} = 0.025 \quad \frac{E_B}{E_G} = 0.4$$

- Courant's number = 0.1
- Resolution: 150×150

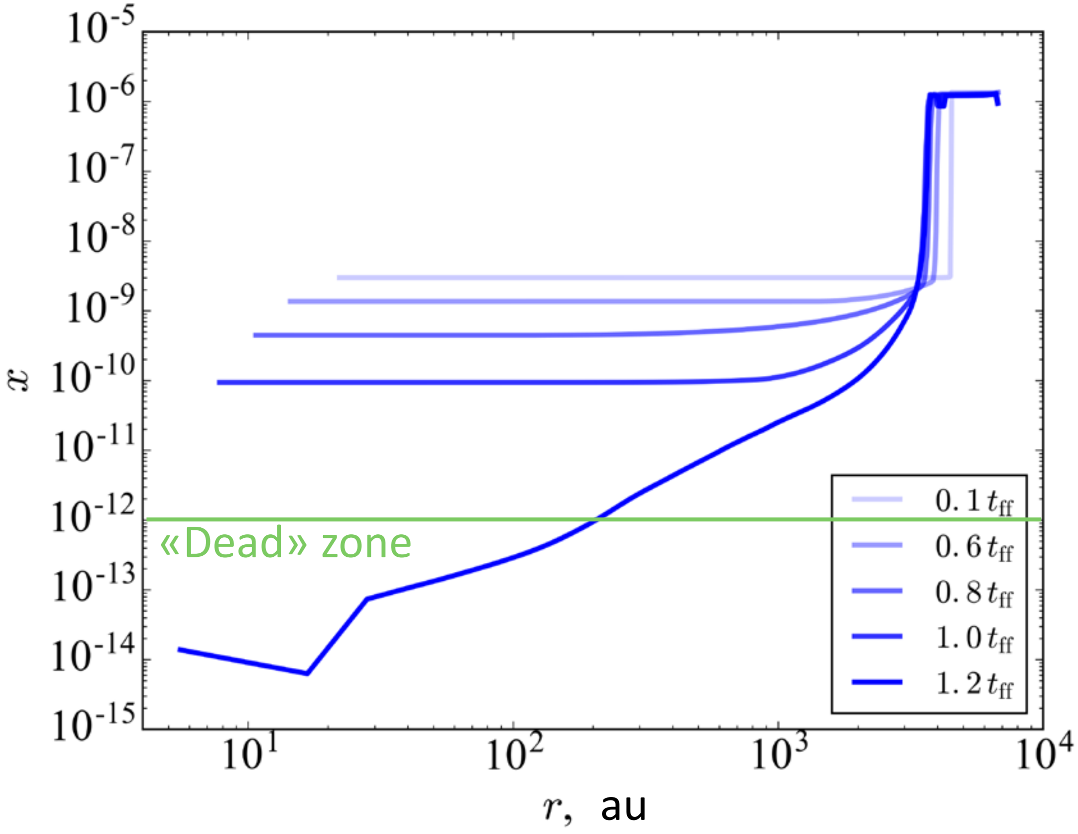
Protostellar disk formation



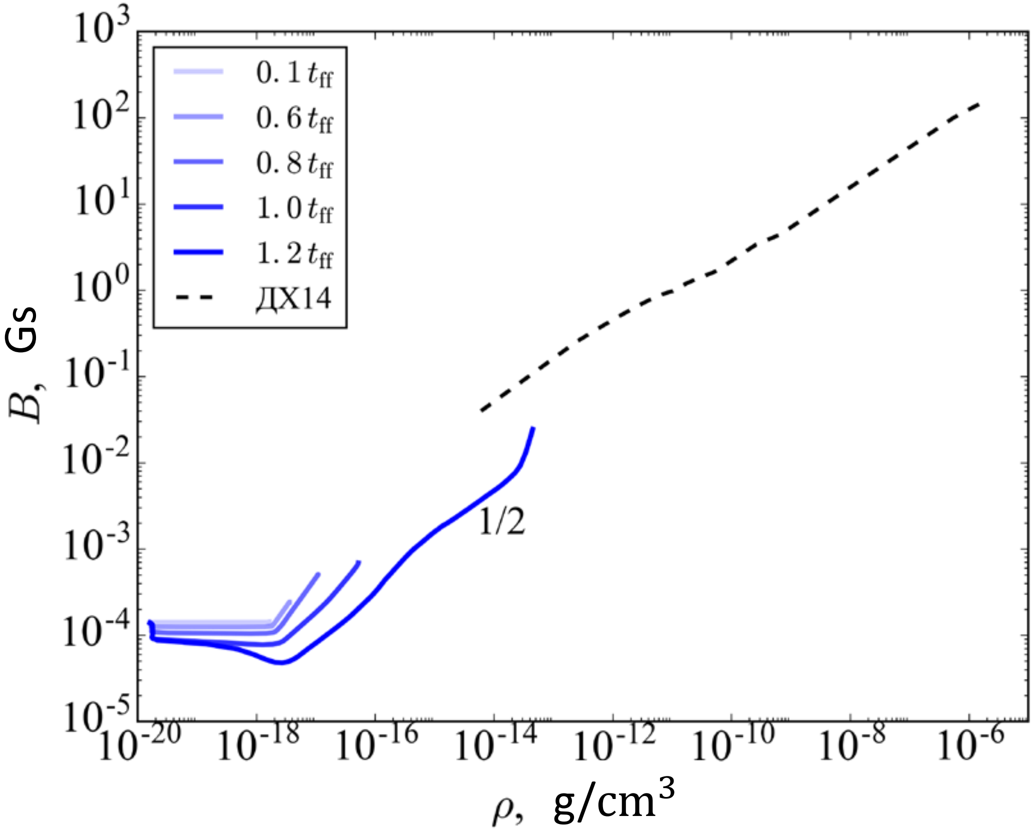
Time: $1.2\ t_{ff} = 5.3 \times 10^4$ years

Flattened envelope with the inner disk is formed

Ionization fraction in the disk



Magnetic field in protostellar disk

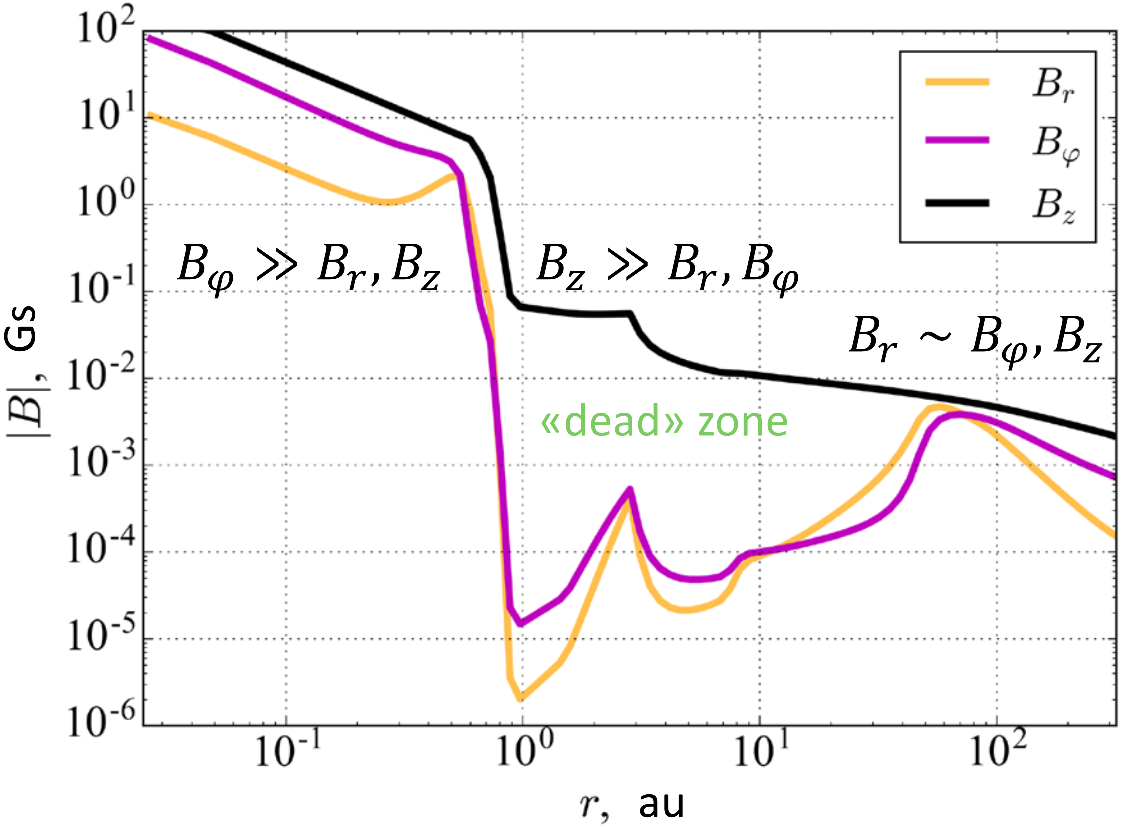


$B \propto \rho^{1/2}$ - magnetostatic contraction

Confirms assumptions of the kinematic MHD model of Dudorov and Khaibrakhmanov[1]

[1] Dudorov, Khaibrakhmanov, 2014, ApSS, 352(1), 103

Magnetic field in accretion disk



$B_\varphi \gg B_r, B_z$

$B_z \gg B_r, B_\varphi$

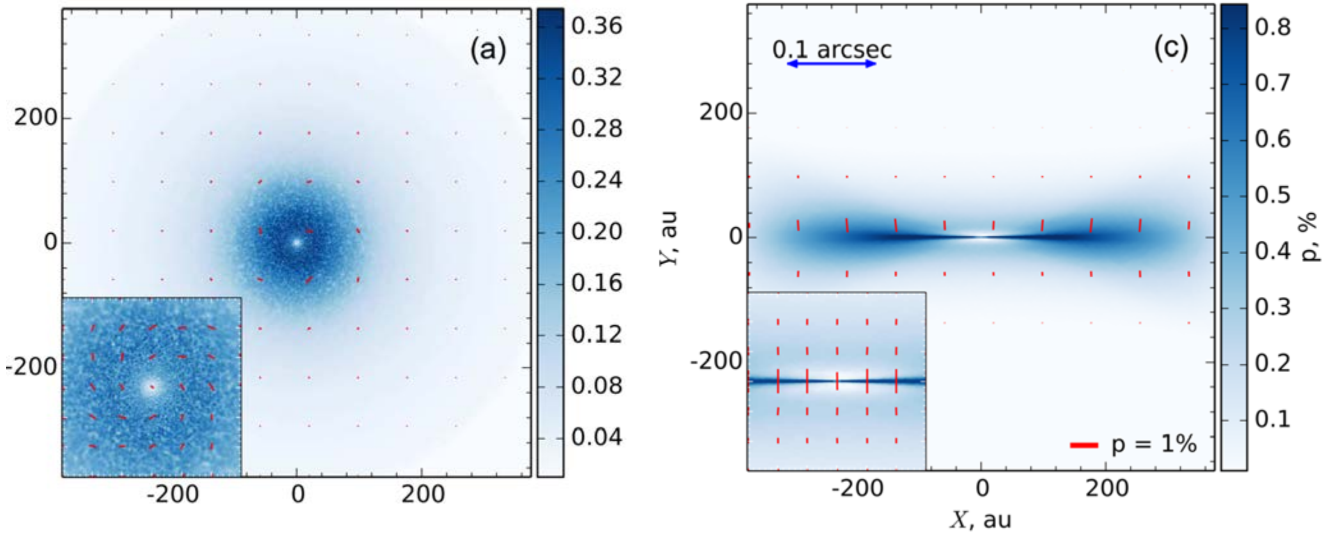
$B_r \sim B_\varphi, B_z$

«dead» zone

Simulation with the help of the kinematic MHD model with Ohmic diffusion, magnetic ambipolar diffusion, buoyancy and Hall effect[1]

[1] Khaibrakhmanov et al, 2017, MNRAS, 454, 586

Synthetic maps of polarized emission 1.3 mm



- «Dead» zone can be observed as the region of lowest polarization fraction

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

Summary

1. We performed simulations of the collapse of the rotating protostellar cloud with strong magnetic field. Ionization model with radiative recombinations and recombinations on dust grains is implemented in the code.
2. The collapse leads to the formation of flattened envelope with the inner disk. Axes ratio of the envelope 1:2, radius of the inner disk – 1000-3000 a.e., height-to-radius ratio of the disk 1:10.
3. Dead zones (region of very low ionization fraction) forms after the protostellar disk formation.
4. Magnetic field intensity depends on density as $B \propto \rho^{1/2}$. In confirms assumptions of the kinematic MHD model of accretion disks of Dudorov and Khaibrakhmanov.

Thank you for your attention!