Dynamics of toroidal magnetic flux tubes in the accretion disks of T Tauri stars

---

Sergey A. Khaibrakhmanov[1,2*], Alexander E. Dudorov[2]

[1]Ural Federal University, Ekaterinburg, Russia
[2]Chelyabinsk State University, Chelyabinsk, Russia

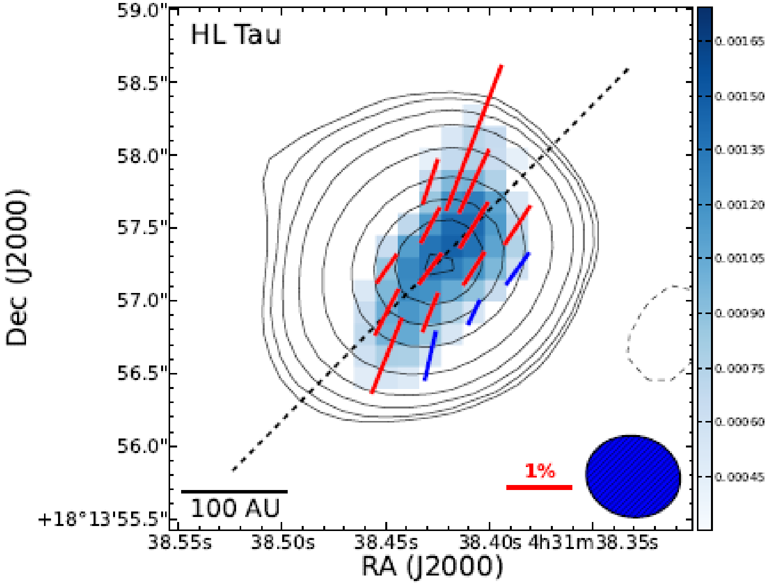
[*]e-mail: khaibrakhmanov@csu.ru

Outline

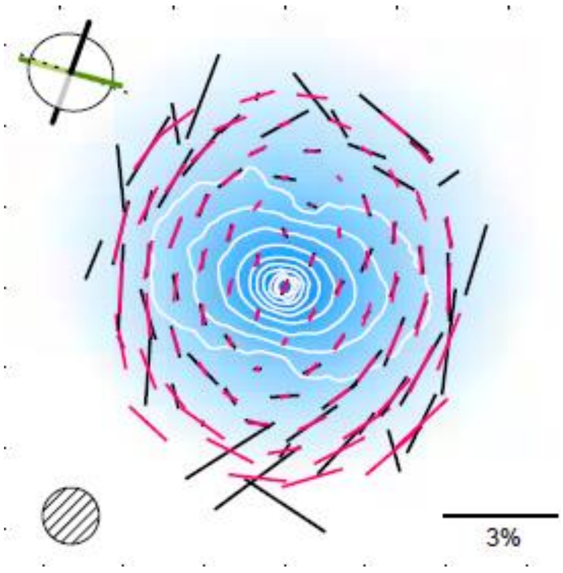
1) Magnetic field in the accretion disks of young stars (ADYS):
   a. Observations
   b. MHD model of the accretion disks
2) Model of the magnetic flux tubes (MFTs) dynamics in the accretion disks
3) MFT dynamics
   a. The case without external magnetic field
   b. Effect of the external magnetic field
4) Comparison with observations
5) Conclusion

Magnetic field geometry in the ADYS

Polarization mapping: signatures of large-scale magnetic field with complex geometry[1,2,3]



[1] Stephens et al, 2014, Nat, 514, 597



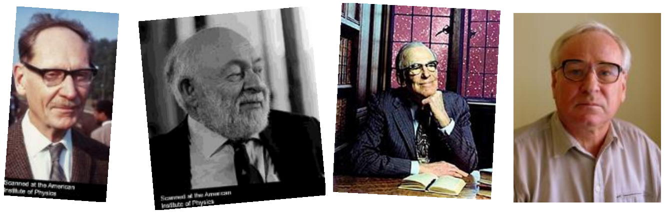
[2] Li et al, 2016, ApJ, 832, 18

[3] Li et al, 2018, MNRAS, 473, 1427

Magnetic field strength in the ADYS

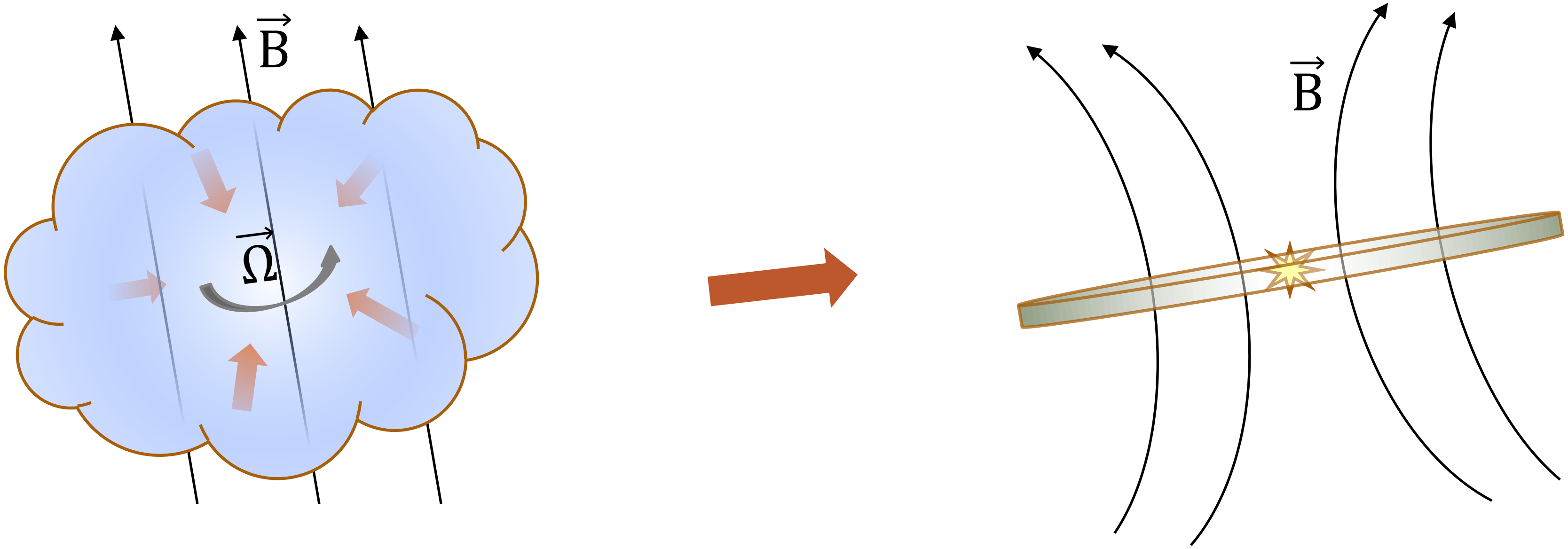
- **Zeeman effect**: indication of a dynamically strong magnetic field near the inner boundary of the FU Ori disk[1]. Measurements of CN circular polarization due to Zeeman splitting are promising[4]
- **Remnant magnetization of meteorites** : indirect constraint of magnetic field strength in the protosolar nebula

B, G	r, au	reference
~ 1000	0.05	[1]Donati et al, 2005, Nat, 438, 466
$0.1 - 1$	3	[2]Levi, 1978, Nature, 276, 481; [3]Fu et al., 2014, Science, 346, 1089
$< 8 \times 10^{-4}$	18	[4]Vlemmings et al. (2019, A&A, 624, L7)



Theory of fossil magnetic field

- Magnetic flux, $\int \vec{B} d\vec{s}$, of the protostellar clouds is partially conserved during the star formation
- ⇒ Magnetic field of the ADYS has a *fossil* nature[1,2]

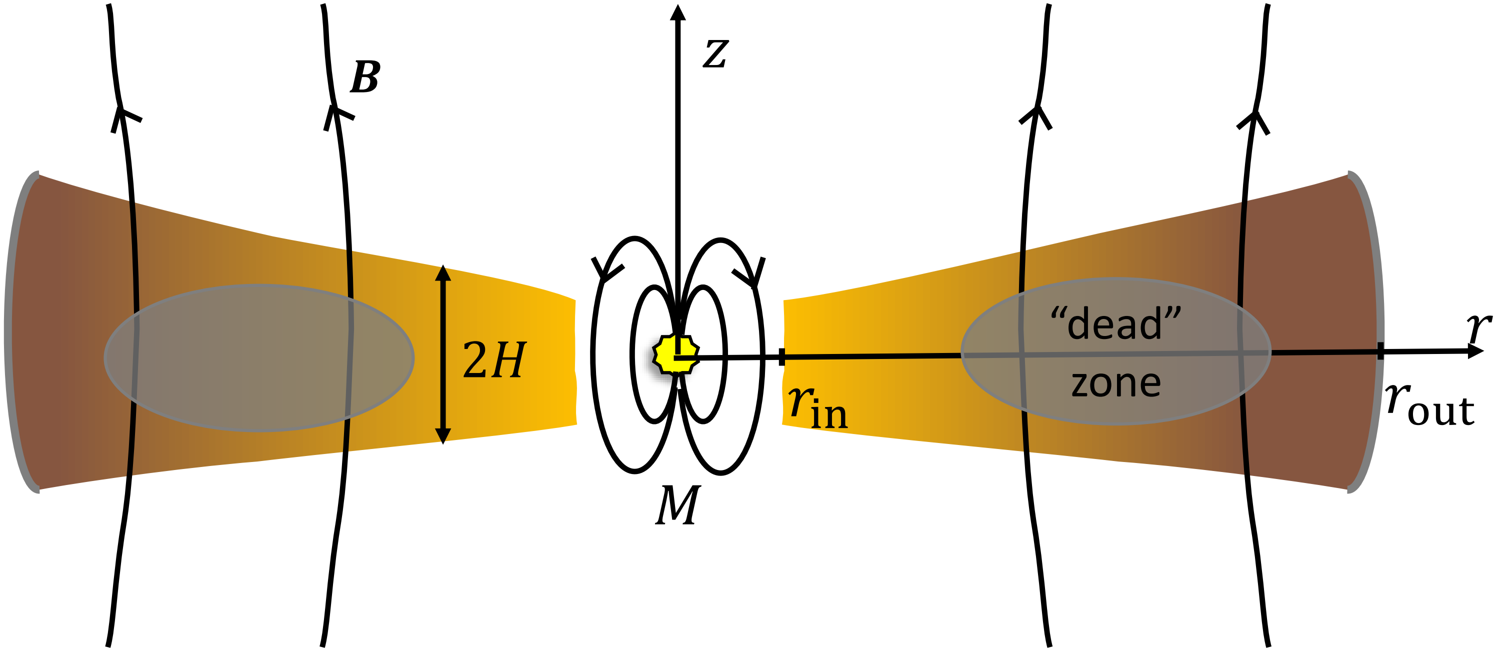


[1] Dudorov, 1995, ARep, 39, 790

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

Magneto-gas-dynamic model of the ADYS

Geometrically thin and optically thick stationary disk with fossil large-scale magnetic field is considered



Dudorov, Khaibrakhmanov, 2014, ApSS, 352, 103;
Khaibrakhmanov et al., 2017, MNRAS, 464, 586

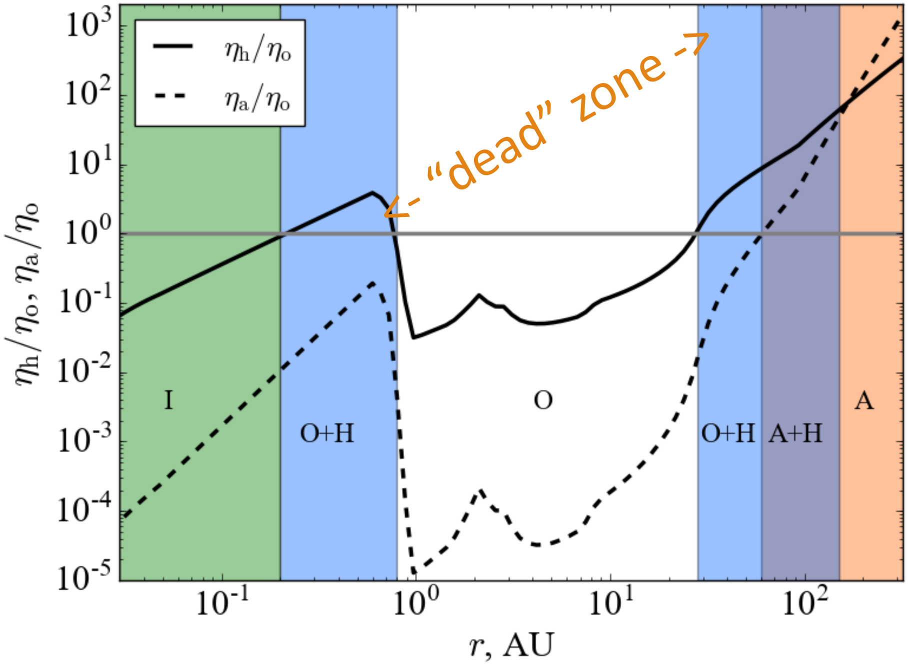
Magneto-gas-dynamic model of the ADYS

- **Radial structure**: equations of Shakura and Sunyaev (1973, A&A, 24, 337) for the case of low temperatures
- **Vertical structure**: hydrostatic equilibrium
- **Ionization fraction**: cosmic and X-rays, radionuclides, thermal ionization, radiative and dissociative recombinations, recombinations onto the dust grains
- **Magnetic field**: induction equation taking into account Ohmic dissipation, magnetic ambipolar diffusion, magnetic buoyancy and the Hall effect
- Inner boundary of the disk: magnetosphere radius, outer boundary: contact boundary with the ISM
- **Analytical solution** for the case of $x \propto n^{-q}$

Dudorov, Khaibrakhmanov, 2014, ApSS, 352, 103;
Khaibrakhmanov et al., 2017, MNRAS, 464, 586

Relative role of the MHD effects in the ADYS

- Typical picture for classical T Tauri star with $M = 1M_{\odot}$, $\dot{M} = 3 \times 10^{-8} M_{\odot}/\mathrm{yr}$, $\alpha = 0.01$
  - $r < 0.5$ au: magnetic field frozen-in gas, $R_m \gg 1$
  - [0.5-30] au: Ohmic dissipation
  - $r >$30 au: ambipolar diffusion
  - $r \sim$1, 30 au: the Hall effect

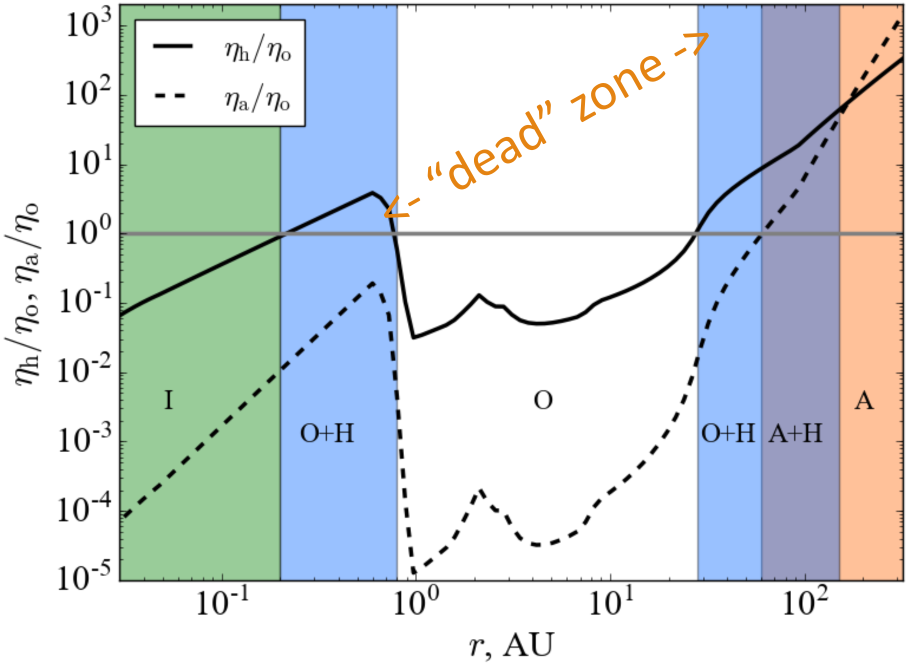


Relative role of the MHD effects in the ADYS

- Typical picture for classical T Tauri star with $M = 1M_{\odot}$, $\dot{M} = 3 \times 10^{-8} M_{\odot}/\text{yr}$, $\alpha = 0.01$

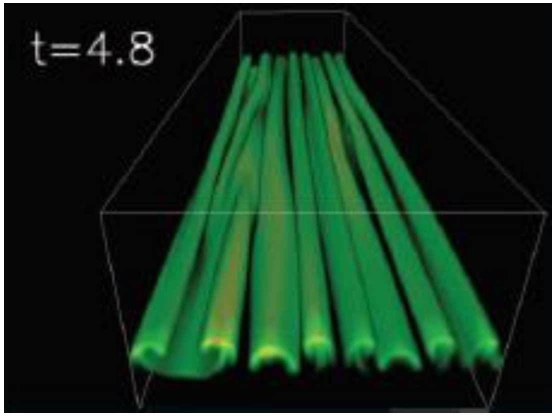
- Intensity of the frozen-in magnetic field grows on the time scale of rotation period in the innermost region, $r < 0.5$ au

- What mechanism could limit runaway growth of the toroidal magnetic field?

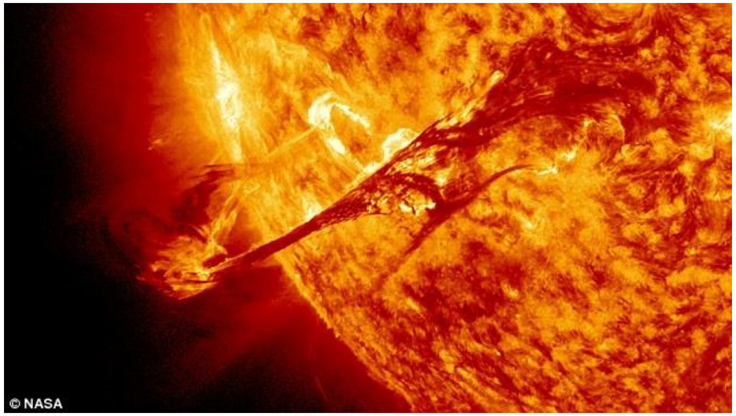


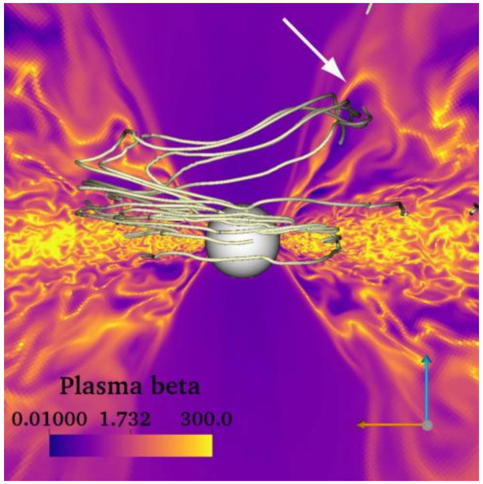
Magnetic buoyancy instability

- Plasma layer with planar magnetic field is unstable and tends to split into magnetic flux tubes (e.g. Parker, 1979)
- Typically, the MFT form if the plasma $\beta \sim 1$
- The MFT are lighter than the surrounding gas and rise under the action of the buoyancy force



Vasil, Brummel, 2008, ApJ, 686, 709

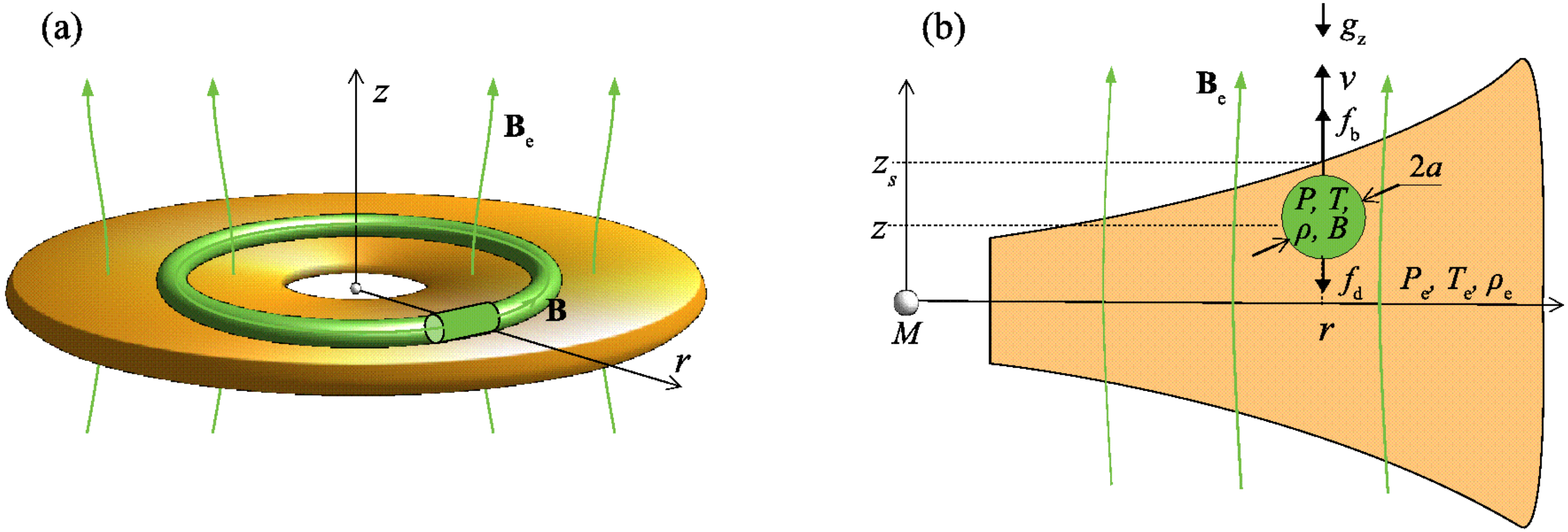




Takasao et al., 2018, ApJ, 857, 4

MFT in the accretion disks

- We consider toroidal MFT formed in the regions of intense B_φ generation
- Dynamics of small length element of the torus is investigated in slender flux tube approximation



Basic equations describing MFT dynamics

$$\begin{aligned}
\rho \frac{dv}{dt} &= (\rho - \rho_e) g_z + f_d \\
\frac{dz}{dt} &= v \\
dQ &= dU + P_e dV \\
P_g + \frac{B^2}{8\pi} &= P_e \\
\frac{dP_e}{dz} &= -\rho_e g \\
M &= \rho \pi a^2 2\pi r \\
\Phi_m &= B\pi a^2 \\
\frac{dv_R}{dt} &= \left(\frac{B_e^2}{2B^2} - 1\right)\frac{B^2}{4\pi\rho}
\end{aligned}$$

The model includes[1,2]:

- Aerodynamic and turbulent drags
- Radiative heat exchange with surrounding gas
- Magnetic field of the disk, B_e

Evolution of major radius of the toroidal MFT is added (Dudorov, 1991, ATsir, 1548, 3)

[1] Khaibrakhmanov, et al., 2018, RAA, 18, 090

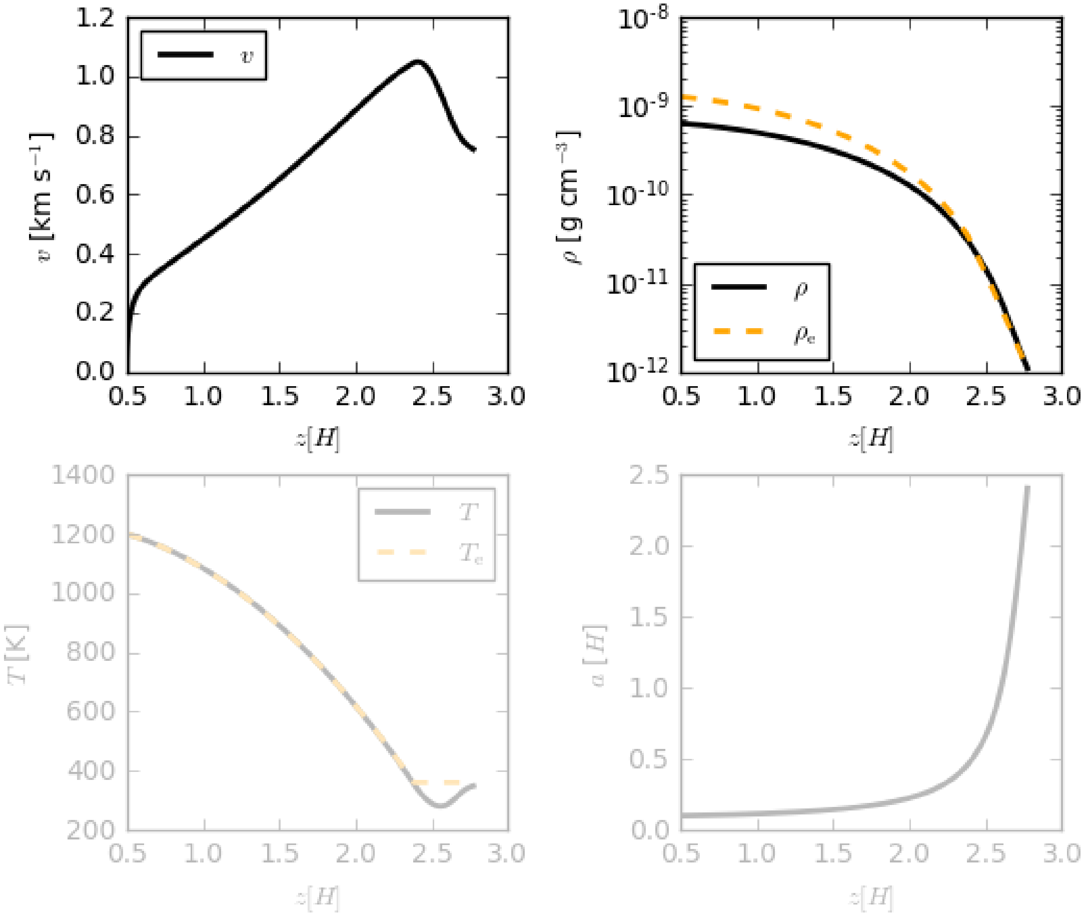
[2] Dudorov, et al., 2019, MNRAS

Model parameters and solution method

- MFT initial parameters:
  - plasma $\beta_0 = 0.01 \div 10$
  - cross-section radius $a_0 = 0.001 - 0.4H$
  - coordinates $r_0 = 0.1 \div 0.6$ au, $z_0 = 0.1 \div 0.5\ H$
  - adiabatic index $\gamma = 7/5$
- Accretion disk of classical TTS: $M = 1M_\odot$, $\dot{M} = 3 \times 10^{-8} M_\odot/\mathrm{yr}$, $\alpha = 0.01$.
- Equations of MFT dynamics are solved using the Runge-Kutta method of the 4th order with automatic step size selection

MFT dynamics without external magnetic field

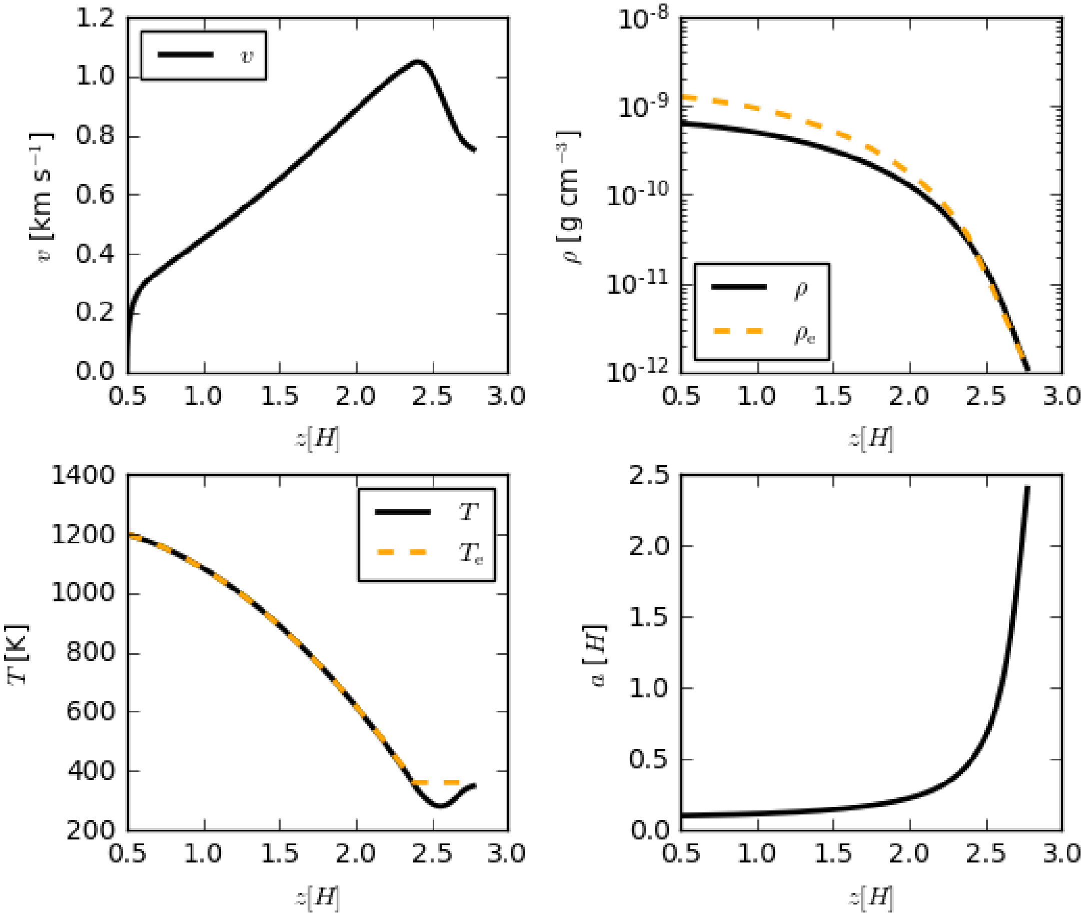
$r = 0.6$ a.e., $a_0 = 0.1H$, $\beta_0 = 1$



The MFT rises from the disk, decelerates near disk surface and acquires terminal speed ~ 0.8 km/s

MFT dynamics without external magnetic field

$r = 0.6$ a.e., $a_0 = 0.1H$, $\beta_0 = 1$

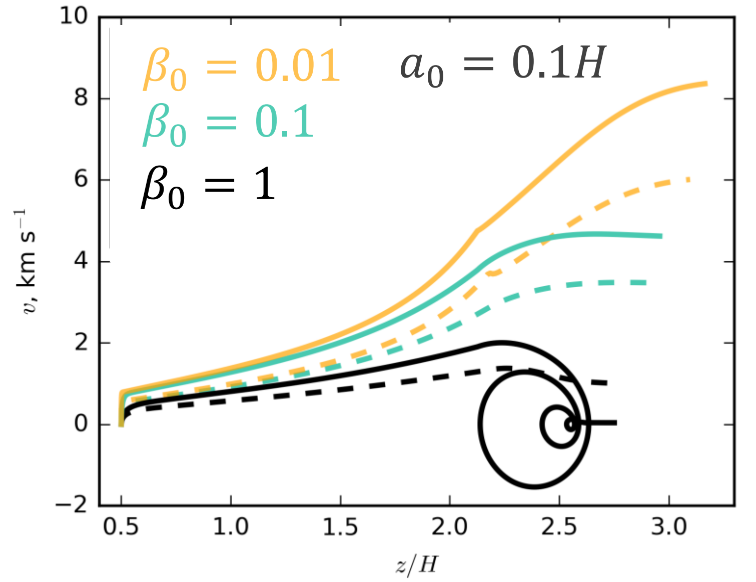


The MFT rises from the disk, decelerates near disk surface and acquires terminal speed ~ 0.8 km/s

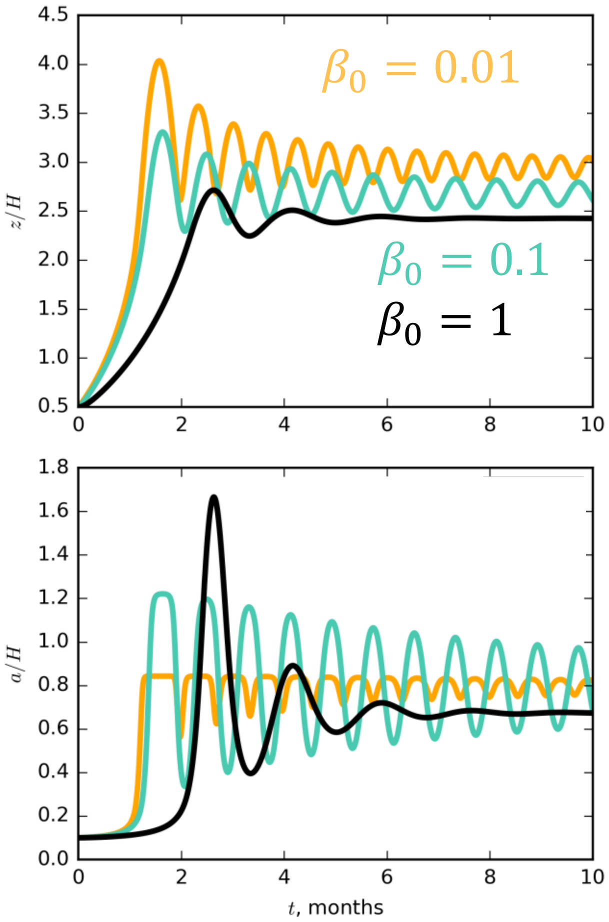
The MFT significantly expands above the disk ⇒ formation of outflowing magnetized corona

Rise velocity of the MFT

- Terminal MFT velocity increases with β_0 and a_0
- The MFT of radii $a_0 \sim 0.1H$ and $\beta_0 \sim 1$ experience several periods of **thermal oscillations** due to adiabaticity and inefficient heat exchange with surrounding gas



Effect of the external magnetic field



Pressure balance taking into account fossil magnetic field of the disk

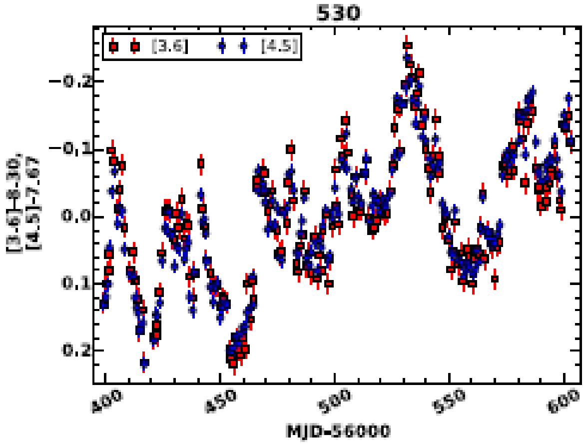
$$P_g + \frac{B^2}{8\pi} = P_e + \frac{B_e^2}{8\pi}$$

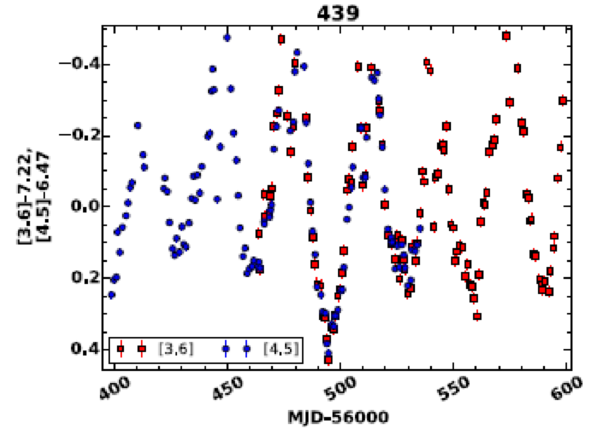
MFT magnetic field decreases during upward motion, but $B_e = const$
⇒MFT oscillates near the point $B = B_e$, where $\rho - \rho_e = 0$.

The **magnetic oscillations** frequency increases with increasing B_0

Connection to observations: variability

- Many young stars exhibit variability
  - IR and optical: on time scales of 1-100 days (see Flaherty et al., 2016, ApJ, 833, 104; Rigon et al., 2017, MNRAS, 465)
  - Variable extinction (see Tambovtseva, Grinin, 2008, A.Lett., 34, 231)
- Causes of variability:
  - Star spots (stellar rotation period)
  - Companion perturbation
  - Variable accretion (days-weeks)
  - Disk warping (dippers, 1-15 days)
  - Periodical changes in the disk thickness (Turner, 2010, 708, 188)





Comparison with the observations

Parameters of classical TTSs in Chameleon 1 cluster[1] and corresponding disk characteristics calculated with our MHD model of the disks. Region with refractory dust is considered

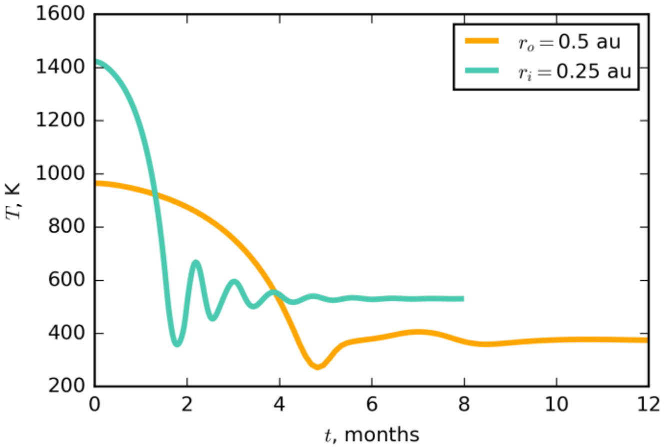
ID	$M_\star$ $[M_\odot]$	$\dot{M}_{-8}$	$L_\star$ $[L_\odot]$	$T_\star$ [K]	$R_\star$ $[R_\odot]$	P [d]	r [au]	$\rho_e(z=0)$ $[\mathrm{g\ cm^{-3}}]$	T_e [K]	H [au]	B_e [G]
439	0.6	4.8	0.8	3669	2.2	32	0.25 0.5	7.3×10^{-9} 1.6×10^{-9}	**1475** **1000**	0.0095 0.0320	13.8 0.24
530	0.63	0.2	0.64	3955	1.7	35	0.07 0.12	1.6×10^{-8} 4.3×10^{-9}	**1463** **996**	0.0013 0.0028	20.4 0.19

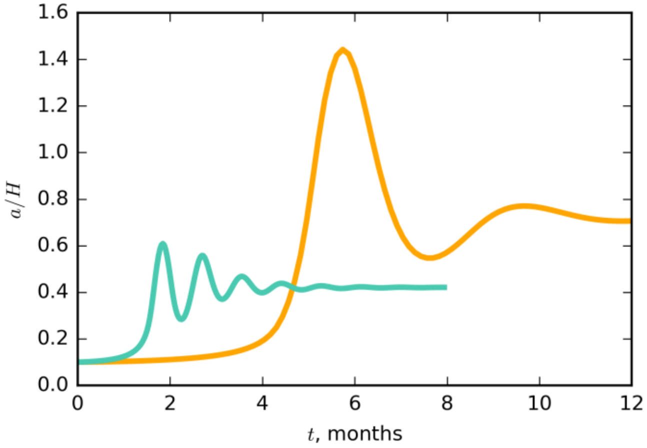
[1] Flaherty et al., 2016, ApJ, 833, 104

Comparison with the observations

- Variations of the MFT temperature and radius in the accretion disk of star 439, the case of $a_0 = 0.1H$, $\beta_0 = 1$: $\Delta T < 300$ К, $\Delta a < 0.8H$

- Optical thickness estimation $\tau = 2a\rho\kappa$: for $\kappa = 0.1\ \mathrm{cm}^2/\mathrm{g}$ $30 < \tau < 75$





Conclusion

- Dynamics of the MFTs consists of two stages: generation due to magnetic buoyancy instability and subsequent rise from the disk. The MFTs rise from the ADYS **periodically** (0.5-10 yrs) with velocities up to 15 km/s and form **non-uniform** outflowing magnetized corona
- Fossil magnetic field counteracts MFT rise. The MFTs experience **magnetic oscillations with periods 10-100 days** near the disk surface
- IR variability and variable extinction of young stars can be explained by the oscillations of the MFTs in the innermost regions of their accretion disks.
- Accumulation of the MFTs near the disk surface can cause burst phenomena which will appear as aperiodic brightness variations

Thank you for your attention!

The work is supported by Russian foundation for basic research (project 18-02-01067)