Magnetospheric Launching in Star Formation

Miljenko Čemeljić 席門傑

ASIAA/TIARA, Taiwan

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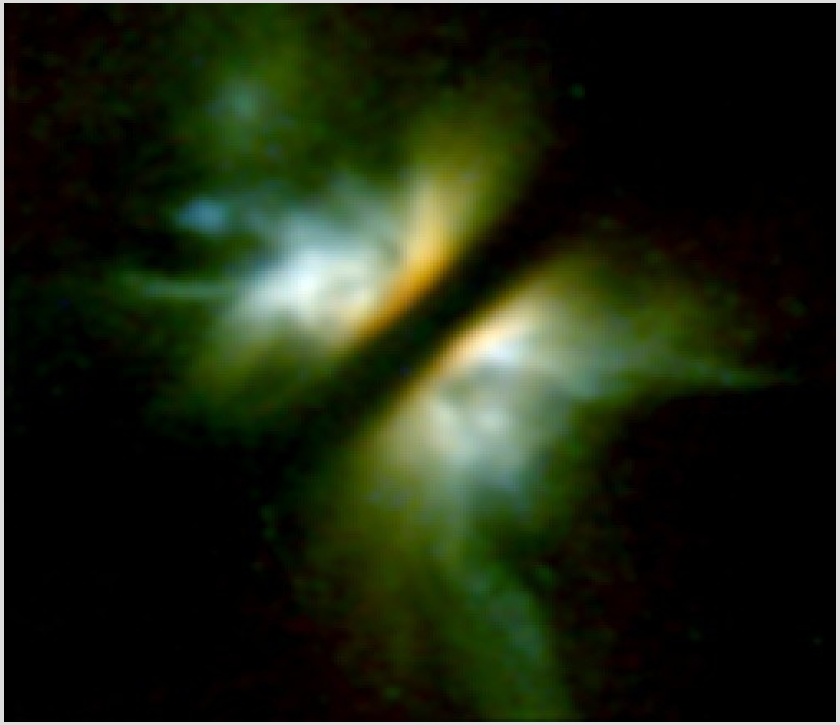
Outline

- Introduction
- Magnetospheric interactions
- Numerical simulations
- Results
- Summary

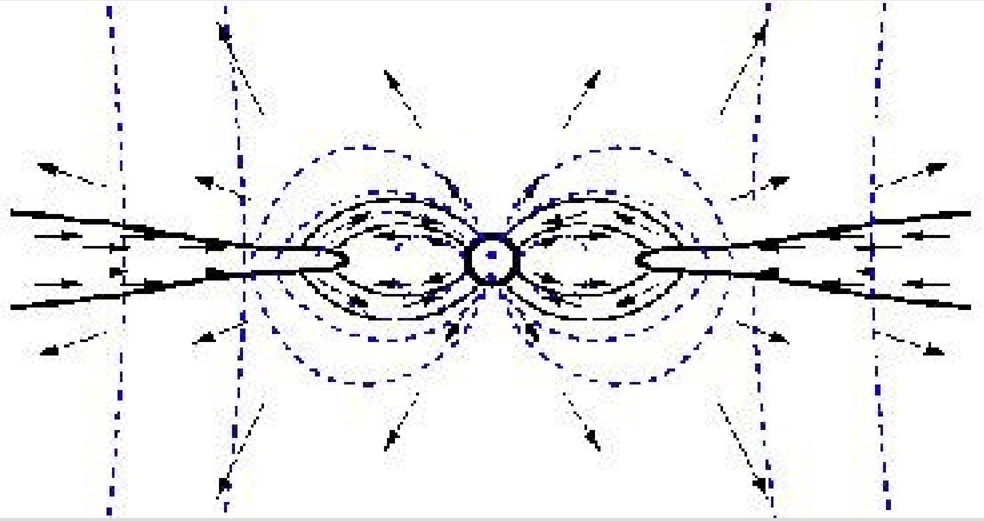
Introduction-observations of young stellar objects



HST-NICMOS camera image of IRAS 04302+2247. Central object is hidden from direct view and seen only by the nebula it illuminates. Disk of dust and gas appears as the thick, dark band crossing the centre of the image. The disk has a diameter of 15 times the diameter of Neptune's orbit, and has a mass comparable to the Solar nebula. Outflows emerge from such objects in various directions.

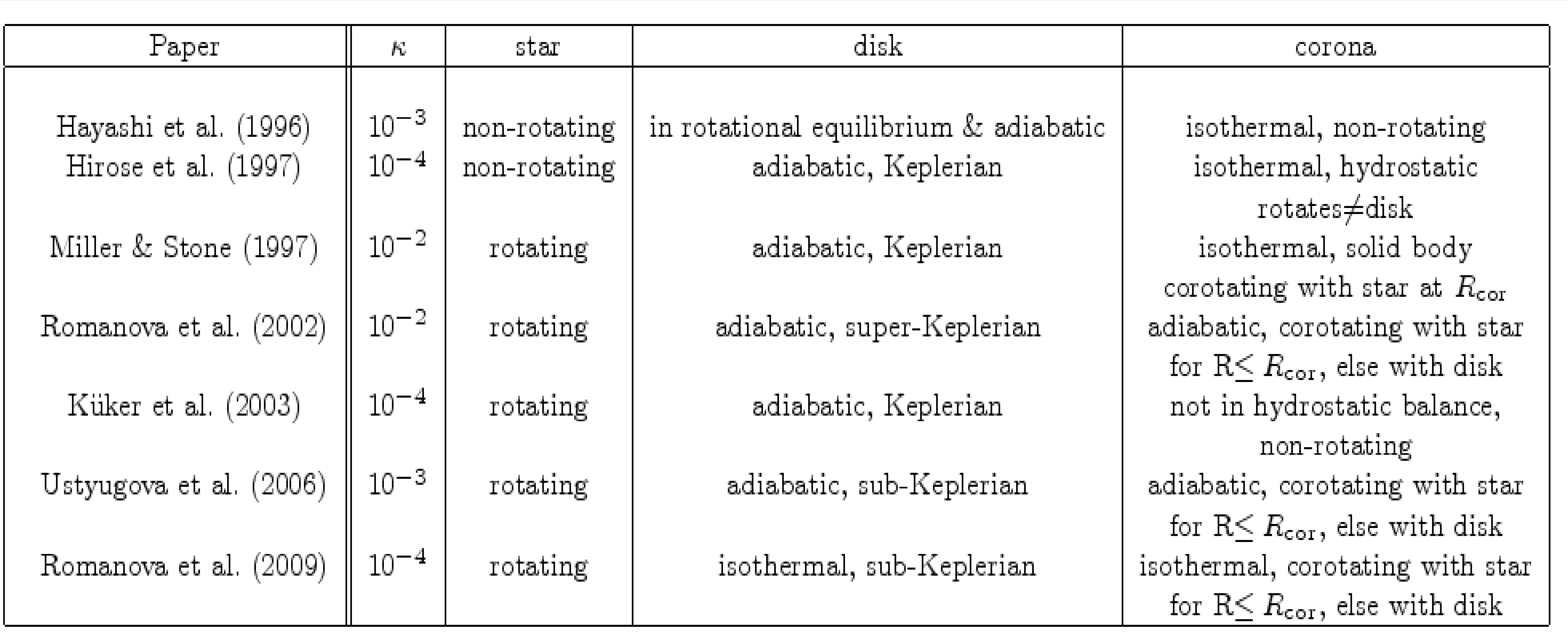
Magnetospheric accretion and ejection of matter

- Outflows extract mass and angular momentum from the system.
- The earliest models invoked stellar wind, following were models with disk wind, both seem to be needed to explain present observations.
- Outflows are fast and collimated (jets) or slower and not collimated. Components are of different mass load and speed, and of different chemical composition.



Star and disk are in interaction via magnetic fields. Most of it happens in the innermost magnetosphere, nearby the disk gap.

Numerical simulations-short overview



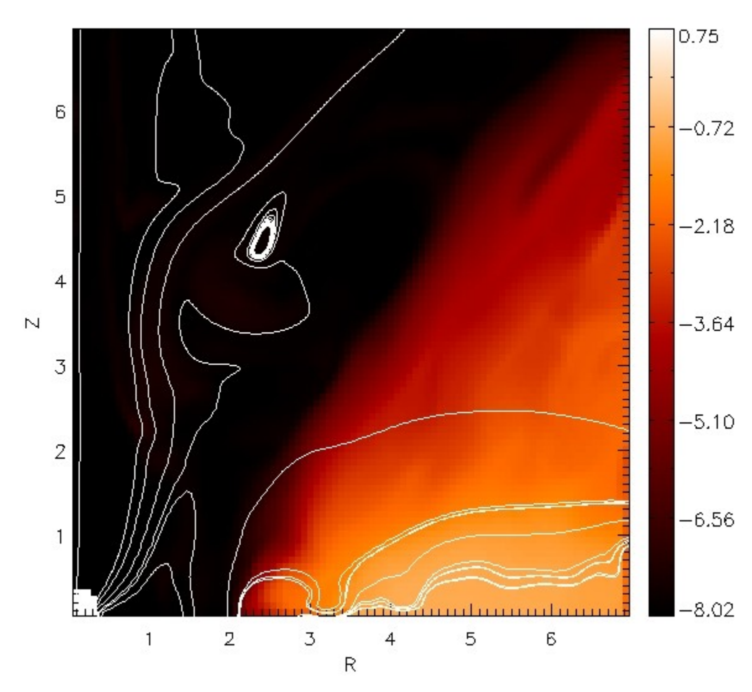
Paper	κ	star	disk	corona
Hayashi et al. (1996)	10^{-3}	non-rotating	in rotational equilibrium & adiabatic	isothermal, non-rotating
Hirose et al. (1997)	10^{-4}	non-rotating	adiabatic, Keplerian	isothermal, hydrostatic rotates$\neq$disk
Miller & Stone (1997)	10^{-2}	rotating	adiabatic, Keplerian	isothermal, solid body corotating with star at $R_{\rm cor}$
Romanova et al. (2002)	10^{-2}	rotating	adiabatic, super-Keplerian	adiabatic, corotating with star for R$\leq R_{\rm cor}$, else with disk
Küker et al. (2003)	10^{-4}	rotating	adiabatic, Keplerian	not in hydrostatic balance, non-rotating
Ustyugova et al. (2006)	10^{-3}	rotating	adiabatic, sub-Keplerian	adiabatic, corotating with star for R$\leq R_{\rm cor}$, else with disk
Romanova et al. (2009)	10^{-4}	rotating	isothermal, sub-Keplerian	isothermal, corotating with star for R$\leq R_{\rm cor}$, else with disk

- How the star slows down? Outflows & jets seem to be helping in this, how? Role of magnetic fields?
- (Too) many models, simulations.

Numerical simulations-problems

- Even when disk is disrupted, it does not launch stationary outflows, collimated or uncollimated.
- In models and simulations, stellar rotation rate often increases, instead of decreasing.

-What are we doing here? Where is jet?



Our numerical simulations-setup

Zeus347

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

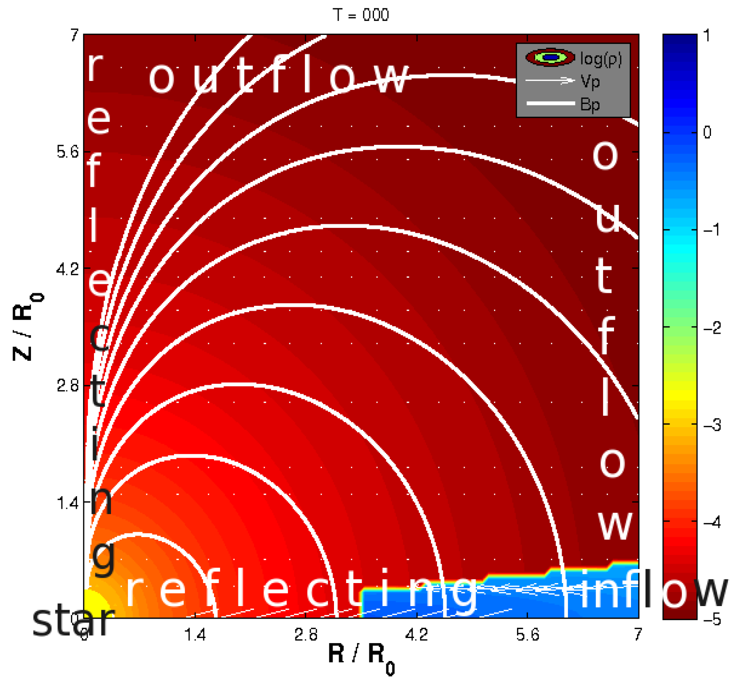
$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] + \nabla p + \rho \nabla \Phi - \frac{\boldsymbol{j} \times \boldsymbol{B}}{c} = 0 \quad (2)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times \left(\mathbf{v} \times \boldsymbol{B} - \frac{4\pi}{c} \eta \boldsymbol{j} \right) = 0 \quad (3)$$

$$\rho \left[\frac{\partial e}{\partial t} + (\mathbf{v} \cdot \nabla) e \right] + p (\nabla \cdot \mathbf{v}) = 0 \quad (4)$$

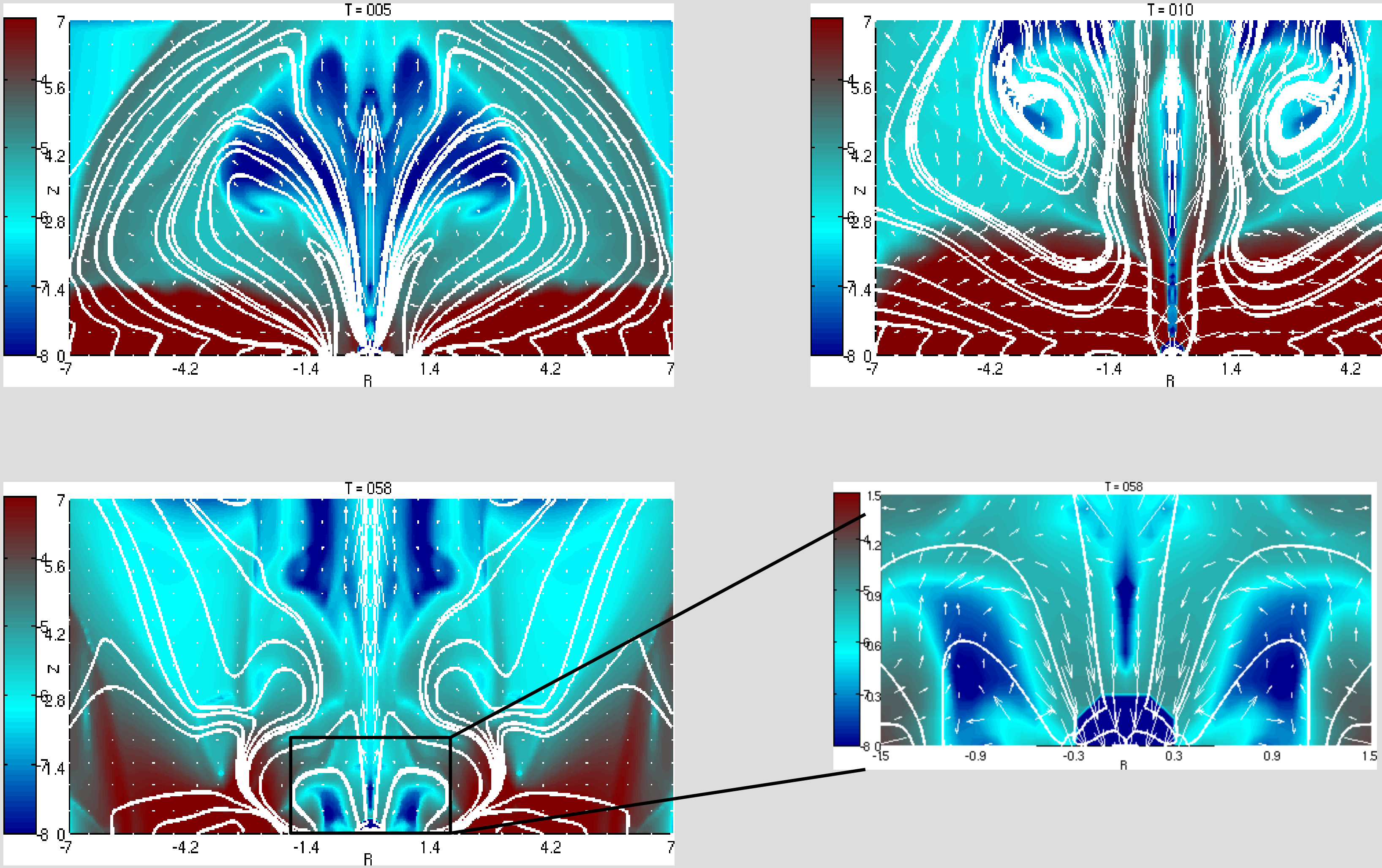
$$\boldsymbol{j} = \frac{c}{4\pi} \nabla \times \boldsymbol{B} \ . \quad (5)$$

entropy S=$\ln(p/\rho^{\gamma})$, with adiabatic index γ=5/3. The internal energy (per unit volume) is then $e = p/(\gamma - 1)$. In corona $\eta = \eta_0 \ \rho^{1/3}$



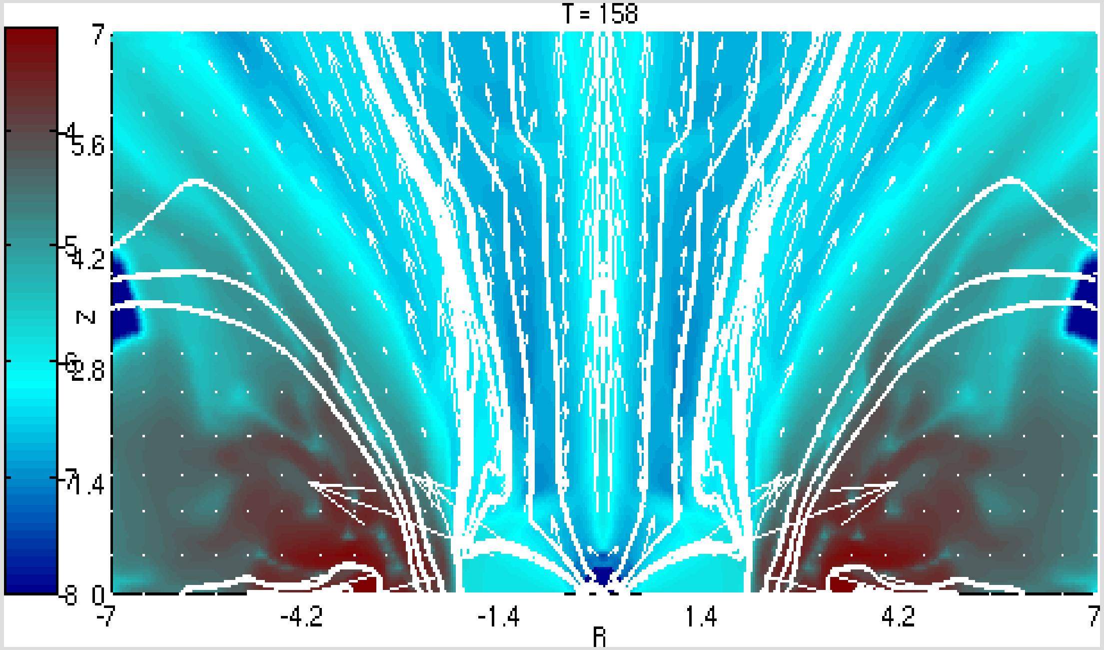
- Innermost region of the star-disk system, RxZ=0.2x0.2 AU
- In the disk, resistivity is constant. Only artificial viscosity is included.
- Two regimes:
  -For R_cor > R_i slow rotating star
  -For R_cor < R_i fast rotating star

Results for slow rotating star - *mass fluxes* in the first three stages



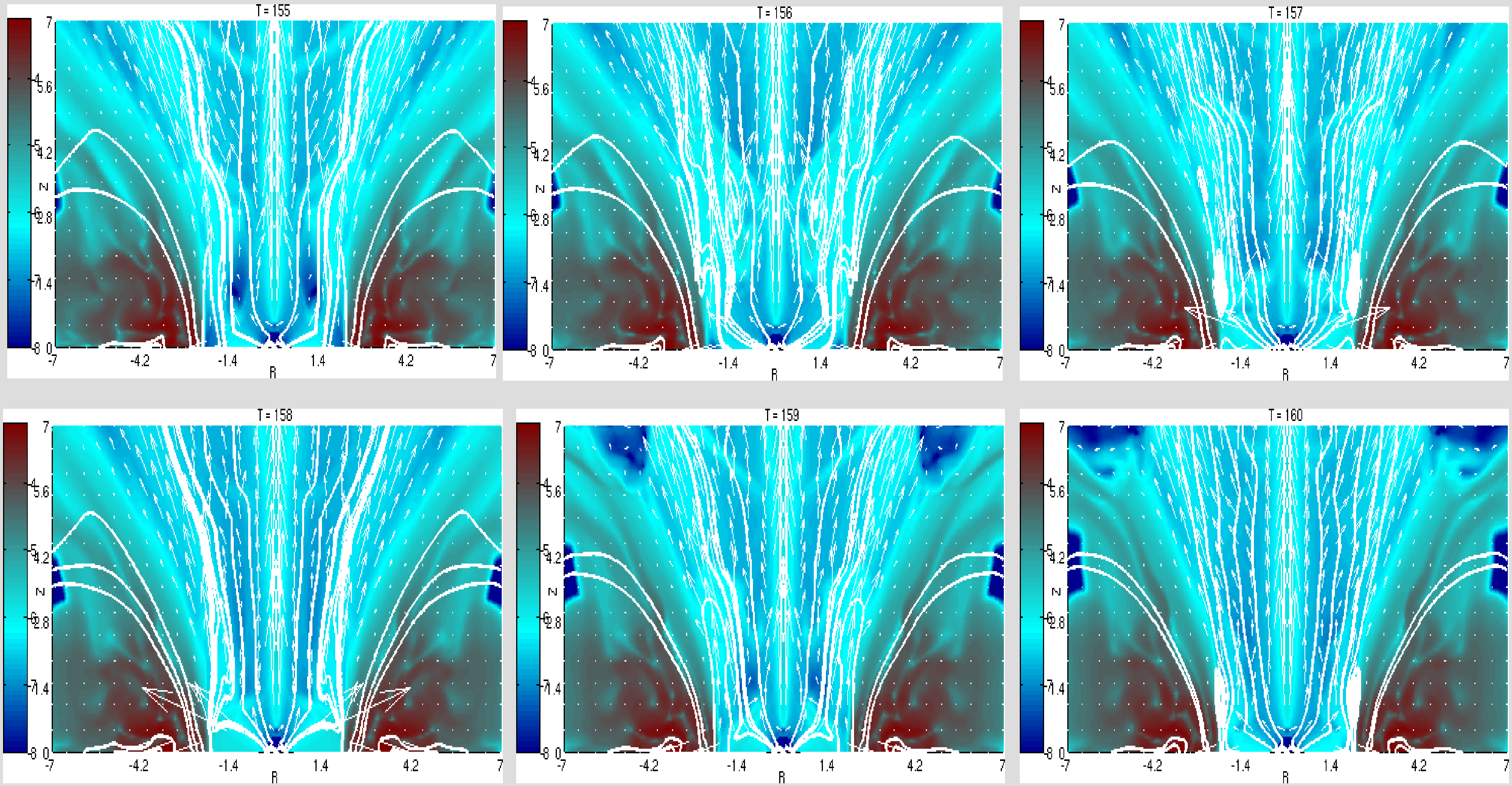
- We find four stages in evolution of star-disk sistem. Shown are mass fluxes.

Results for slow rotating star-final stage



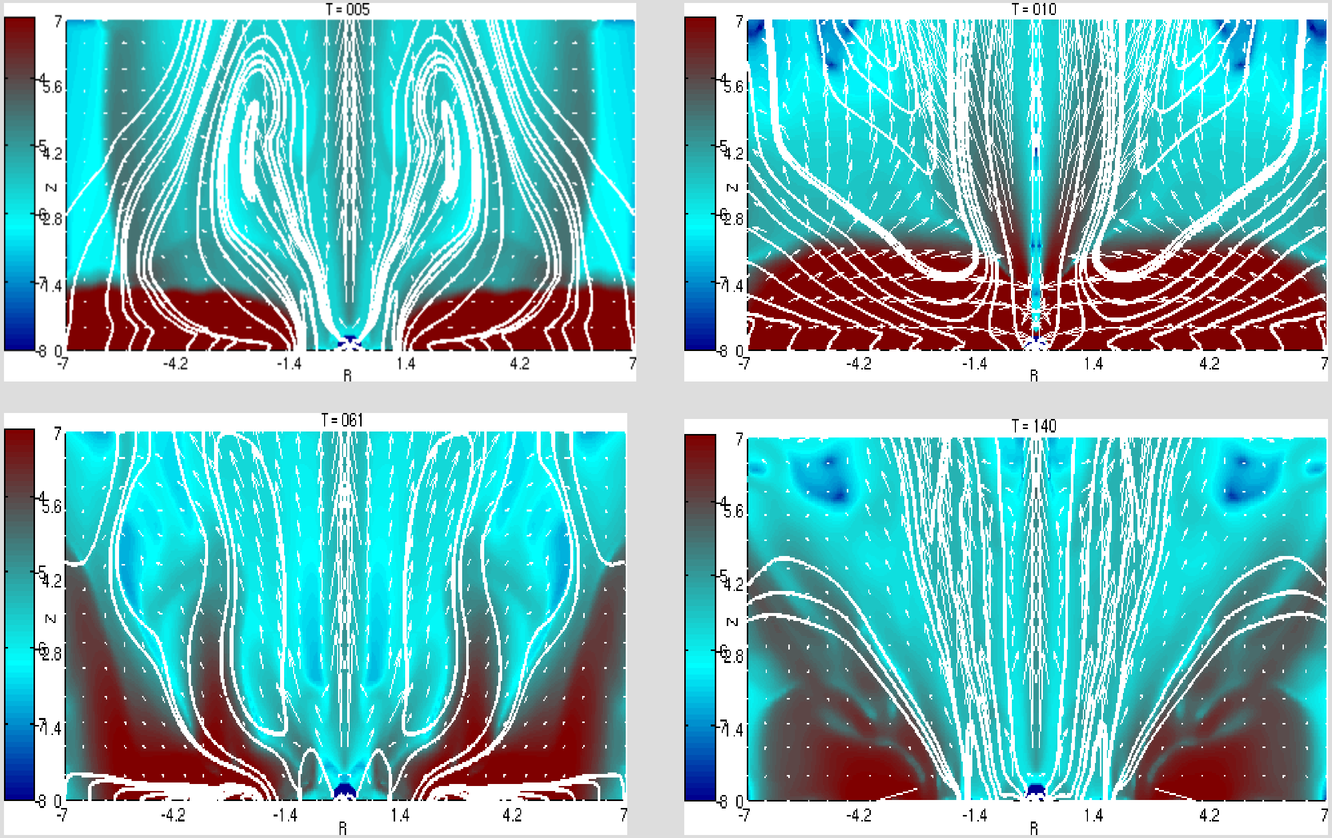
- Two quasi-stationary components: fast, collimated axial outflow and slower, dense conical outflow.
- How “stationary” are they?

Final stage quasi-stationarity



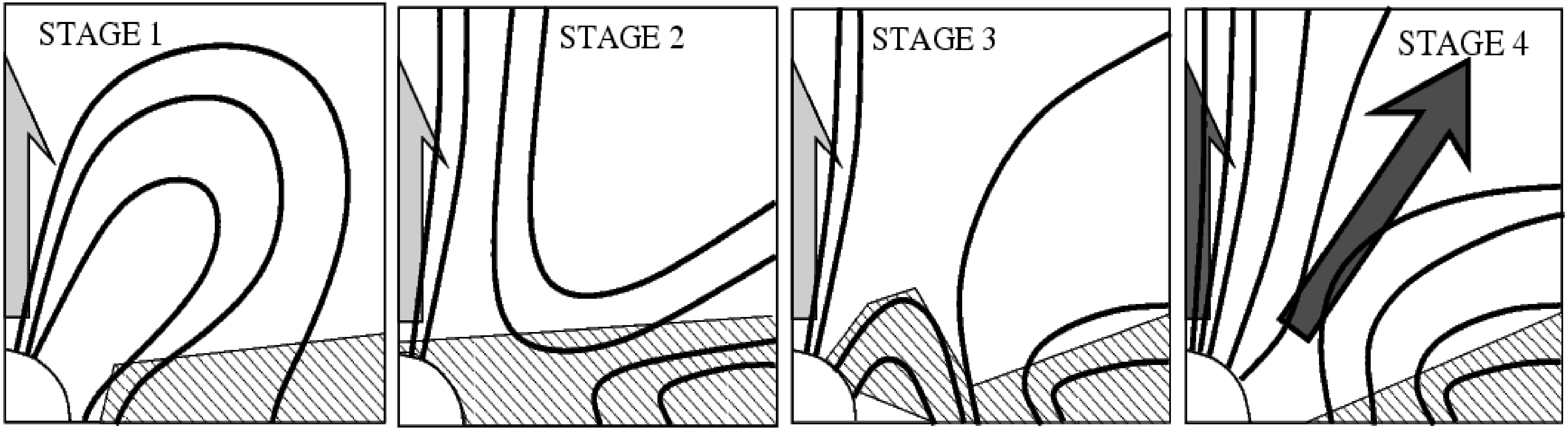
- *Quasi*-stationary two-component outflow.

Results for fast rotating star



- Results are similar to slow rotating star case.

Geometry of magnetic field in 4 stages of evolution



- All simulations of star-disk interaction in our setup go through four stages: 1) relaxation with pinching of mag. field inwards, 2) reconnection and opening of the stellar dipole, 3) narrowing of the disk gap, formation of transient funnel flow onto the stellar surface, 3) final stage of equilibrium of magnetic and disk ram pressure, with two-component outflows, one axial and another conical.
- Arrows depict components of outflow.

Reconnection of magnetic field

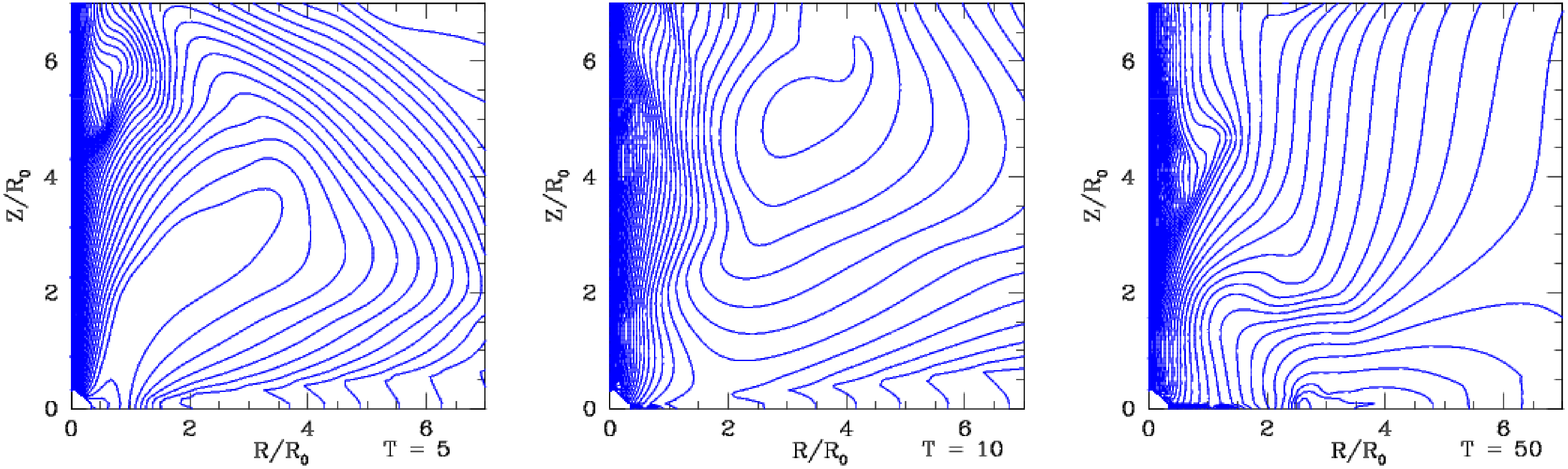
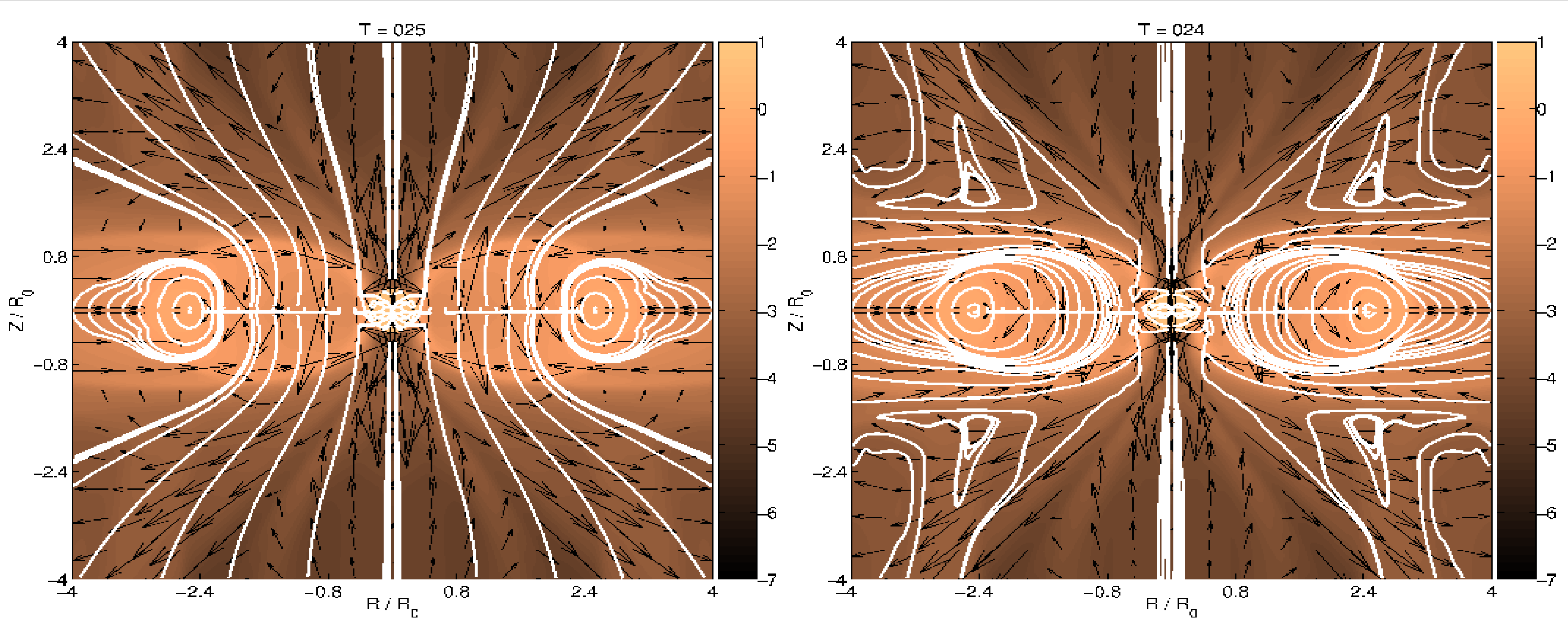


FIG. 12.— The reconnection of magnetic field in our typical solution. Shown are the poloidal magnetic field lines in different timesteps. The initial stellar dipole is pinched by the infalling matter (*Left panel*) and, with help of dissipative processes, which is resistivity in this case, through the reconnection phase (*Middle panel*) reaches the final field geometry, of the open stellar and disk field (*Right panel*).

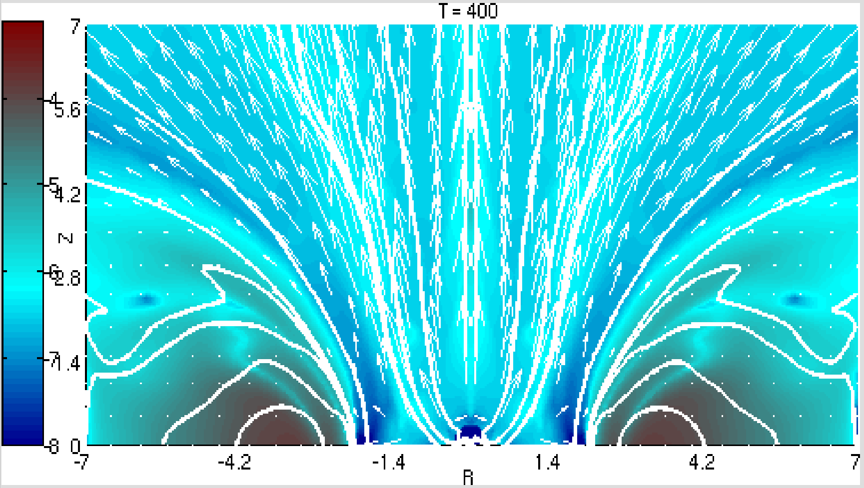
- The first three stages are related to the reshaping of the magnetic field, because of reconnection. Resistivity facilitates reconnection, so that in effect result depends on resistivity in the magnetosphere.

Effect of reconnection on solutions

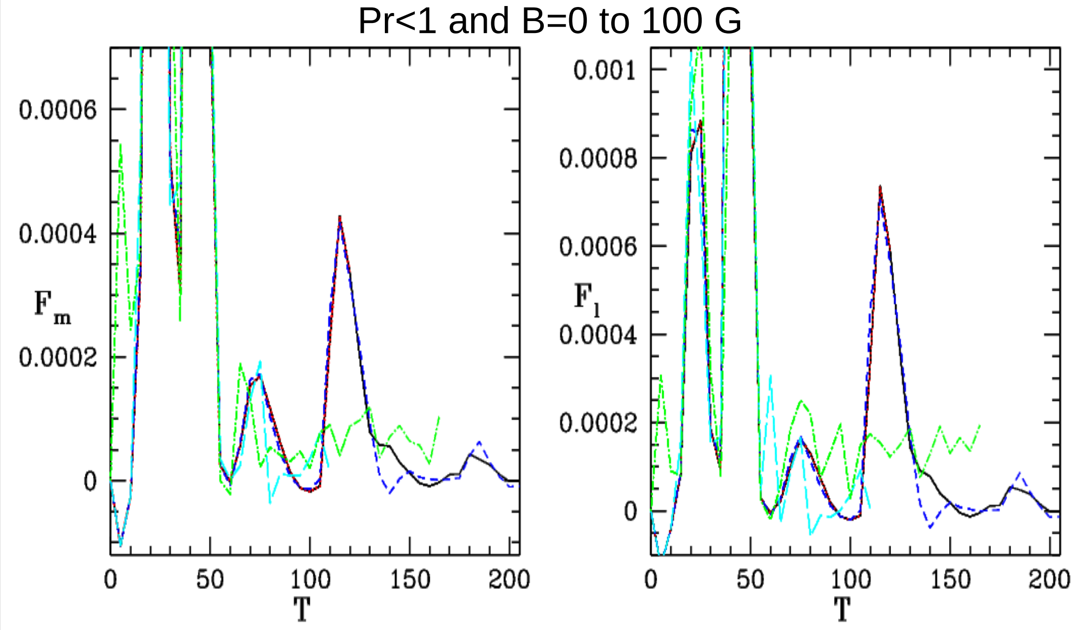


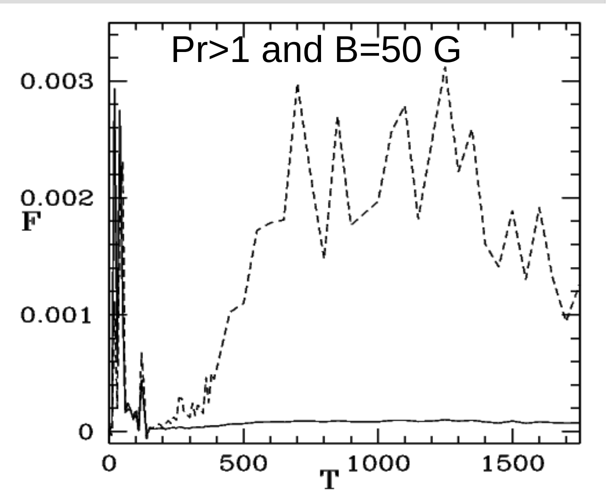
- *Left* is the solution with resistivity in magnetosphere included, R*ight* is without resistivity. The density (color grading) is almost identical in both cases , but magnetic field geometry (solid lines) shows big difference.

Another dissipation process: (artificial) viscosity

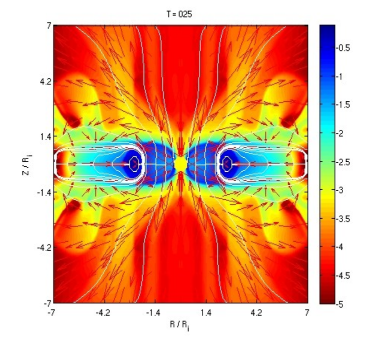


- We also investigate portion of parameter space with Pr=viscosity/resistivity >1.
- Viscosity helps to stabilize the outflow-longer lasting solutions.
- Mass and angular momentum fluxes increase with larger magnetic field. Angular momentum flux increases with larger viscosity.


Pr<1 and B=0 to 100 G


Pr>1 and B=50 G

Summary



- Observations show that there is more than one component in the stellar outflows.
- Recent simulations show that some version of magnetospheric accretion-ejection mechanism is responsible for launching of protostellar outflows and jets.
- We show that resistive simulations alone, without viscosity included, are sufficient for obtaining the two-component outflows.Two components seem to be built-in feature.
- Viscosity helps to stabilize the outflow. Probably best combination is to have both, resistivity and viscosity included in simulations.