Resistive MHD simulations of protostellar outflows

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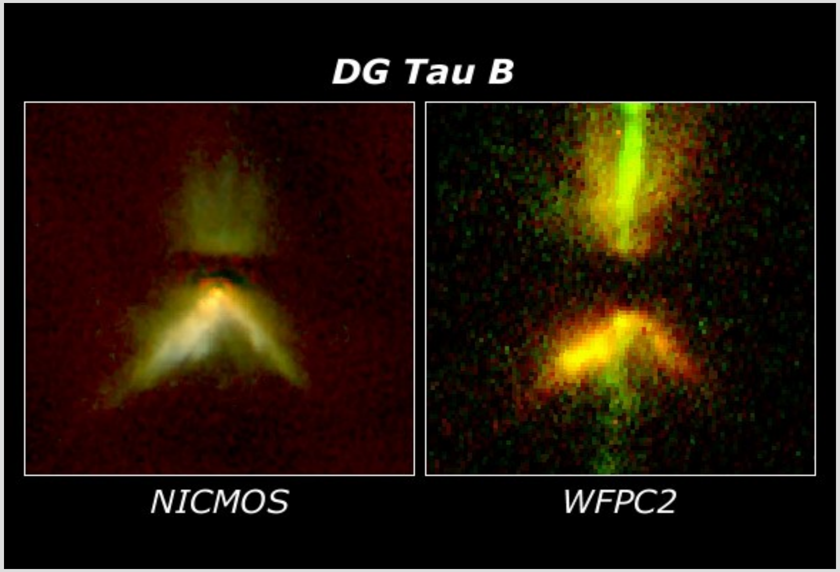
ASIAA/TIARA, Taiwan

Spectroimaging Star Formation Workshop, Taipei, June 20-24, 2011

Outline

- Introduction
- Magnetospheric interactions
- Star-disk simulations
- Summary

Young stellar objects-observations

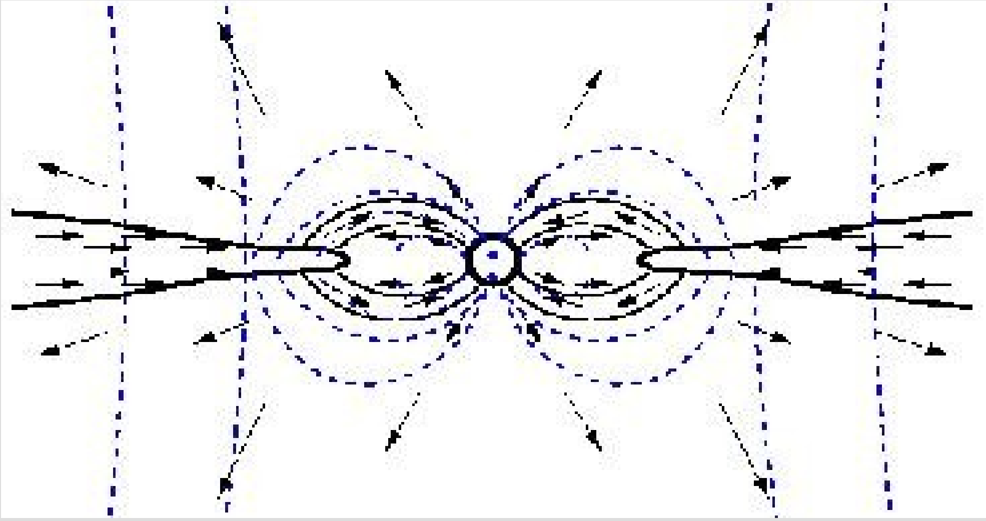


-outflows from Young Stellar Objects are usually shown as launched from the accretion disk, or as stellar wind+disk outflow.

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 it in various directions.

Magnetospheric accretion and ejection of matter

- Outflows extract mass and angular momentum from the system.
- The earliest models were about stellar wind, then were models with disk wind, combination of those seems to be needed to explain 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, disk and magnetic fields are in interaction. Most of it happens in the innermost magnetosphere, nearby the disk gap.

Numerical simulations-short overview

TABLE 1
LIST OF ASSUMPTIONS FOR INITIAL CONDITIONS IN SOME RELEVANT WORKS

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_{cor}
Romanova et al. (2002)	10^2	rotating	adiabatic, super-Keplerian	adiabatic, corotating with star for R$\leq R_{cor}$, 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$\leq R_{cor}$, else with disk
Romanova et al. (2009)	10^4	rotating	isothermal, sub-Keplerian	isothermal, corotating with star for R$\leq R_{cor}$, 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, each with its own setup, assumptions.

Dissipation processes: viscosity & resistivity

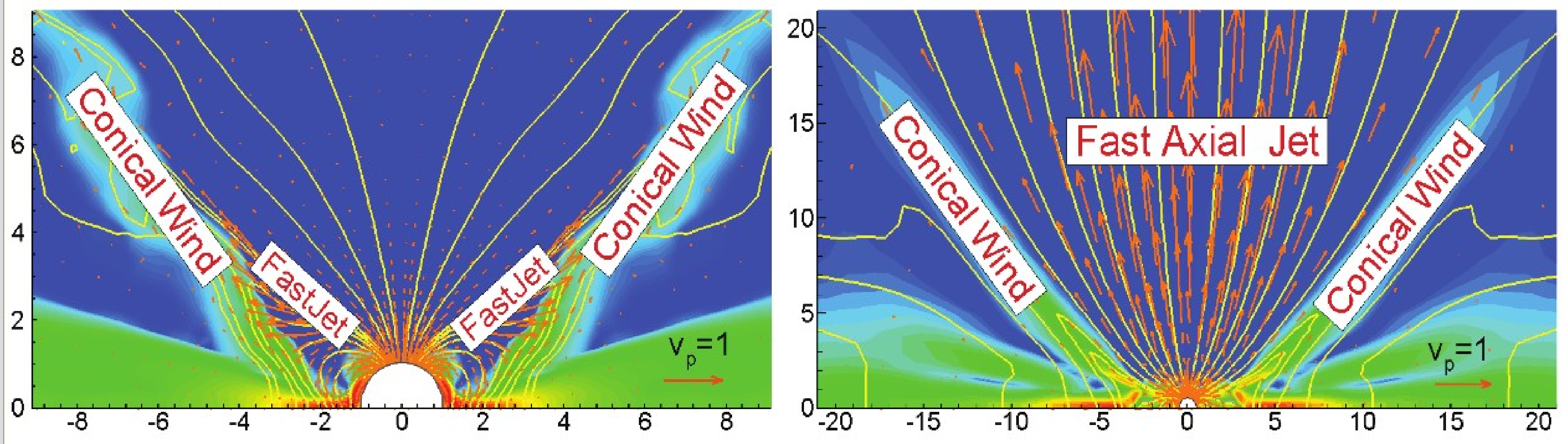


Figure 1. Two-component outflows observed in slowly (left) and rapidly (right) rotating magnetized stars for the reference runs described in this paper. The background shows the poloidal matter flux $F_{\mathrm{m}} = \rho v_{\mathrm{p}}$, the arrows are the poloidal velocity vectors and the lines are the sample magnetic field lines. The labels point to the main outflow components.

- E.g. in Romanova et al. 2009 is investigated portion of parameter space with both physical viscosity and resistivity, with Pr=viscosity/resistivity >1.
- Viscosity helps to stabilize the outflow.
- Mass and angular momentum fluxes increase with larger magnetic field. Angular momentum flux increases with larger viscosity.

Purely resistive simulations

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

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

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

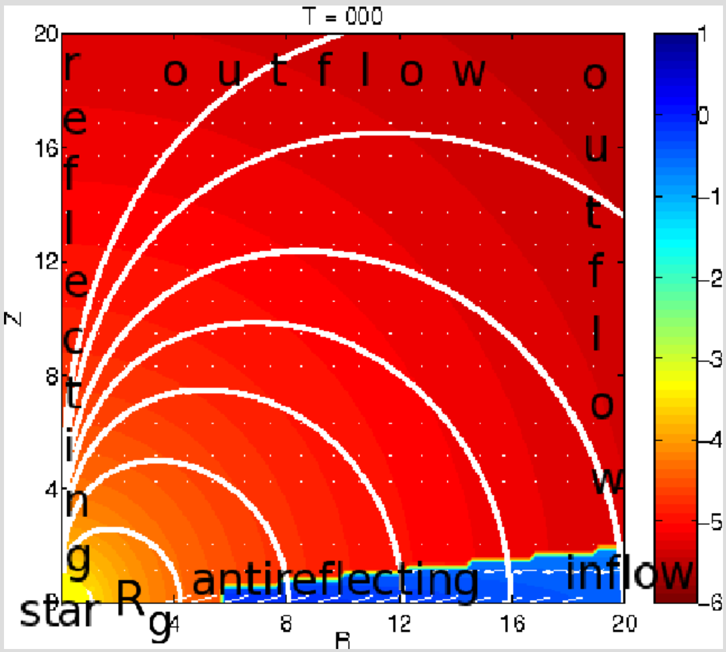
$$\rho \left[\frac{\partial e}{\partial t} + (\mathbf{v} \cdot \nabla)\, e \right] + p(\nabla \cdot \mathbf{v}) = 0 \quad (4)$$

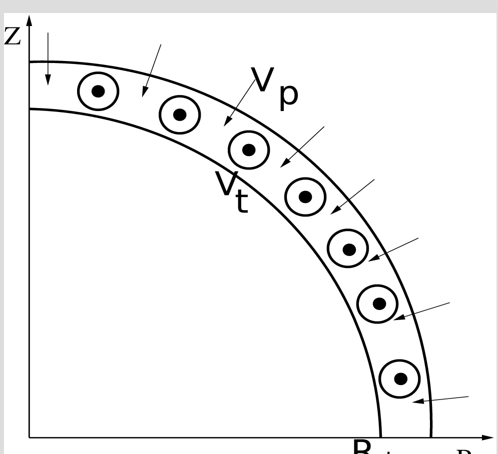
$$\boldsymbol{j} = \frac{c}{4\pi} \nabla \times \boldsymbol{B}\ . \quad (5)$$

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

- Code Zeus347 in 2D & axisymmetry option, purely resistive simulations.
- No physical viscosity, only artificial viscosity is included, for smoothing shocks.
- Two regimes for stellar rotation rate with respect to R_corrotation=(GM/Ω^2)^(1/3):
  -For R_cor > R_truncation “slow” rotating star
  -For R_cor < R_truncation “fast” rotating star

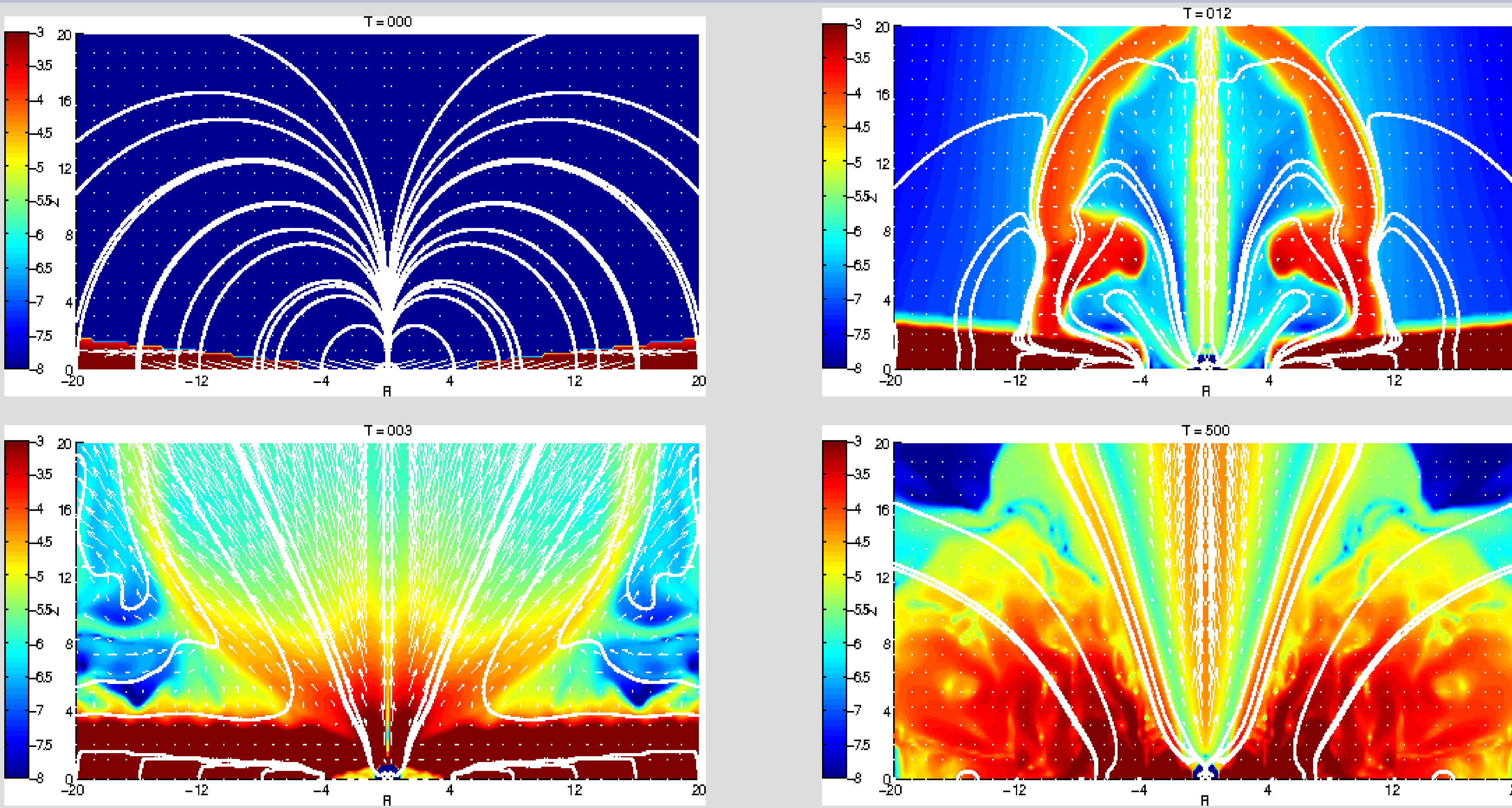
Setup





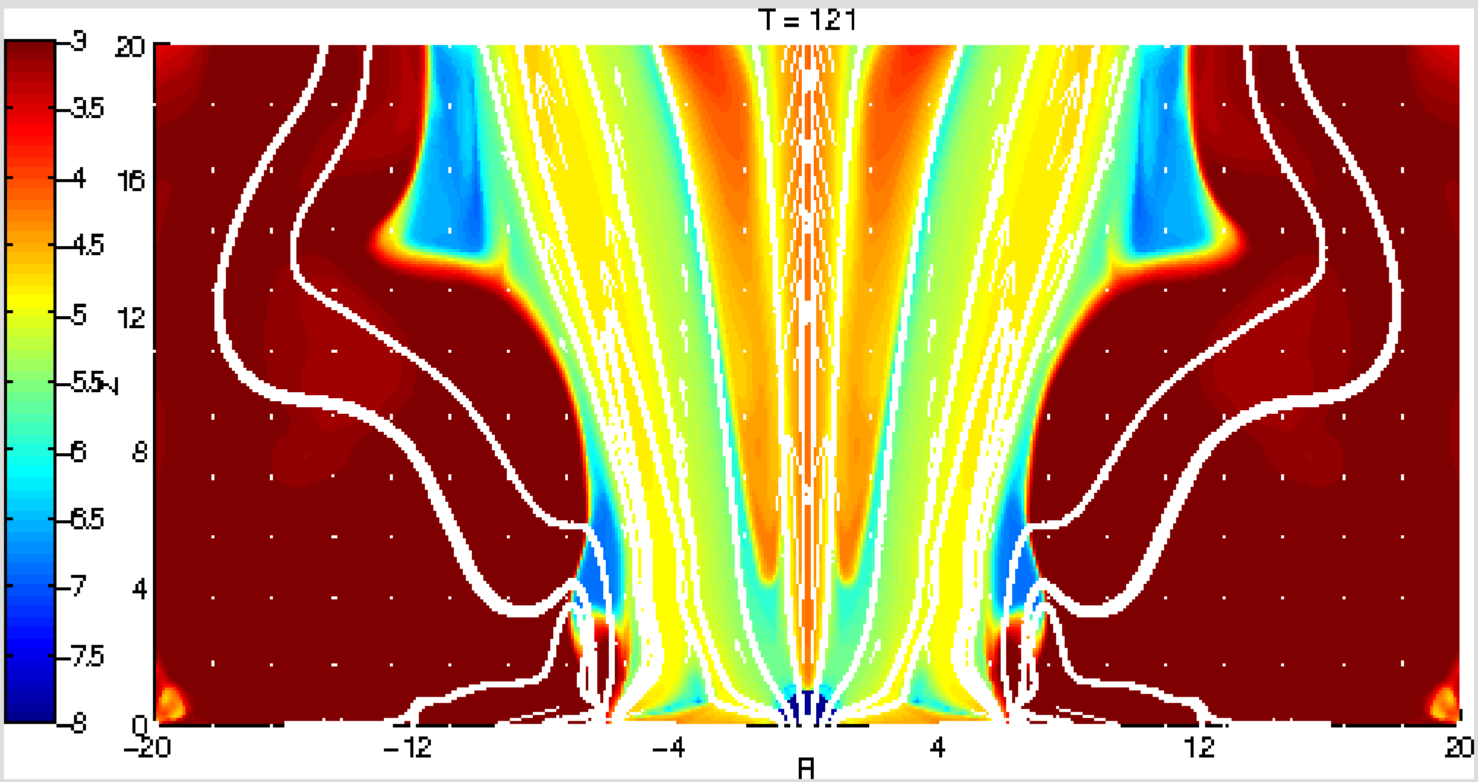
- We are solving for innermost region of the star-disk system, RxZ=(90x90)grid cells=0.2x0.2 AU. Set is a balanced disk in slightly sub-Keplerian rotation, with rotating, hydrostatic corona and dipole magnetic field centered in the origin. Resistivity in the disk is constant, and in corona modeled by density, with $\eta \sim \rho^{(1/3)}$
- Around the origin is set rotating, absorbing layer of stellar radius, which is a sink for matter.
- In simulations with artificially imposed gap, we also set “outflow” condition of length R_g at the disk mid-plane.

Solutions with changing stellar rotation rate



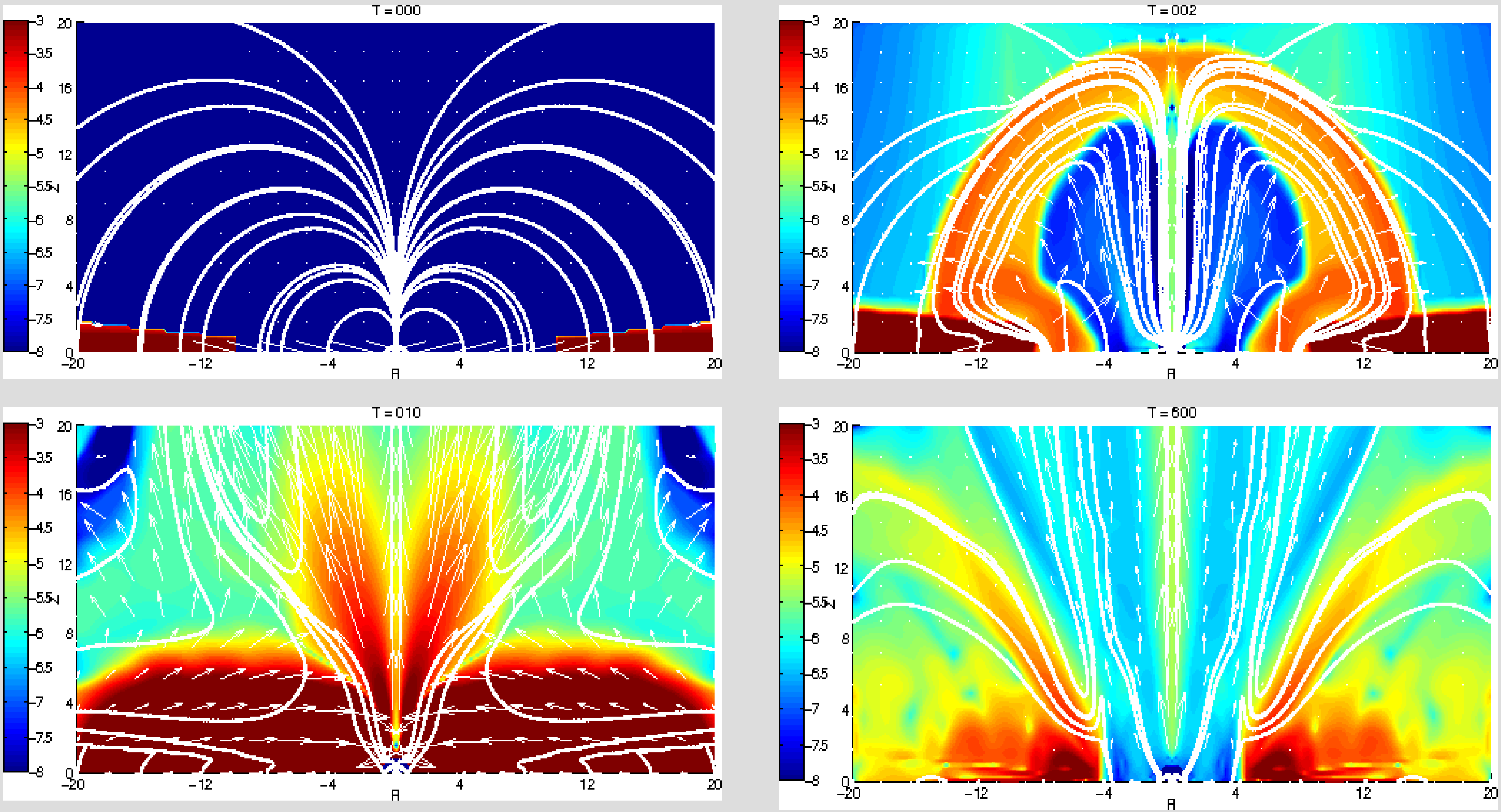
Most general solutions, when stellar rotation rate is allowed to change. Shown are mass fluxes in logarithmic color grading.

Solutions with constant stellar rotation rate



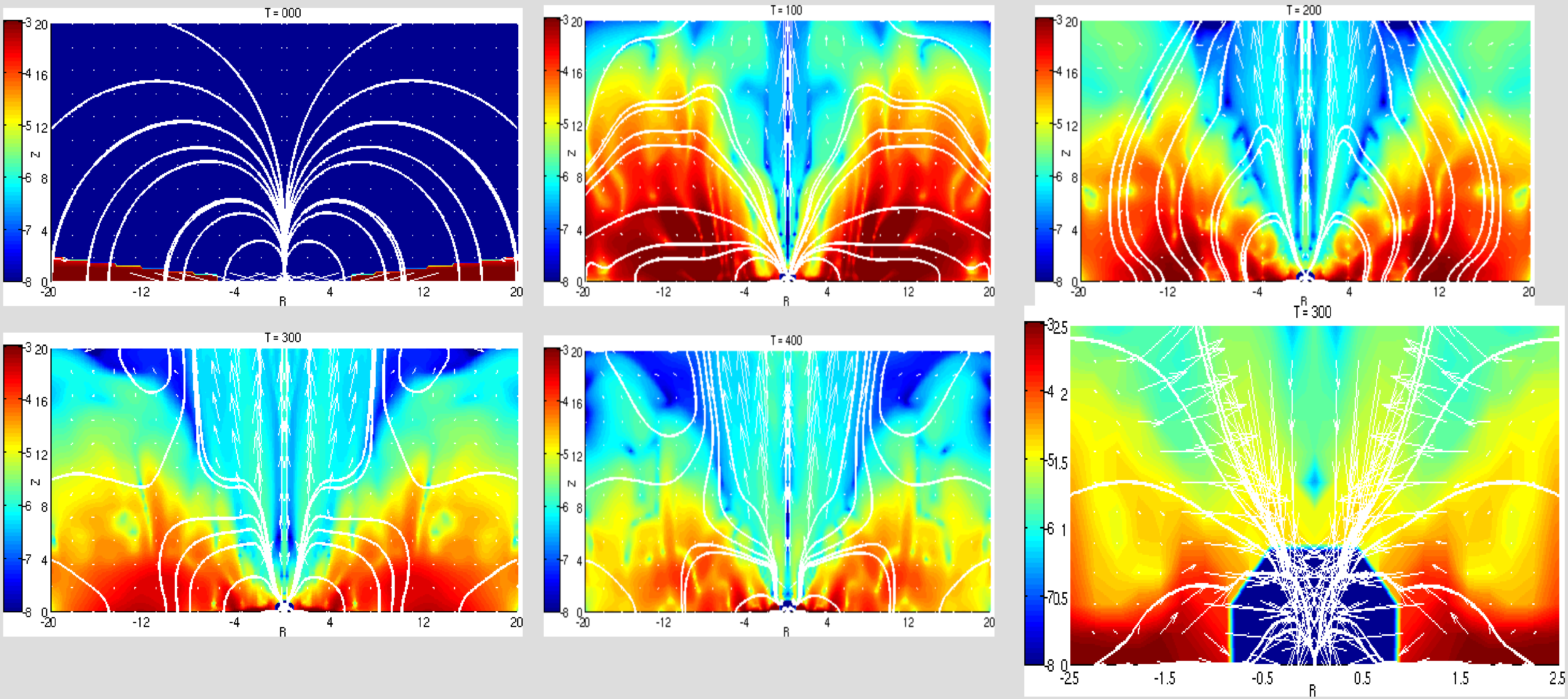
Solution when stellar rotation rate is kept constant throughout the simulation.

Solutions with imposed gap



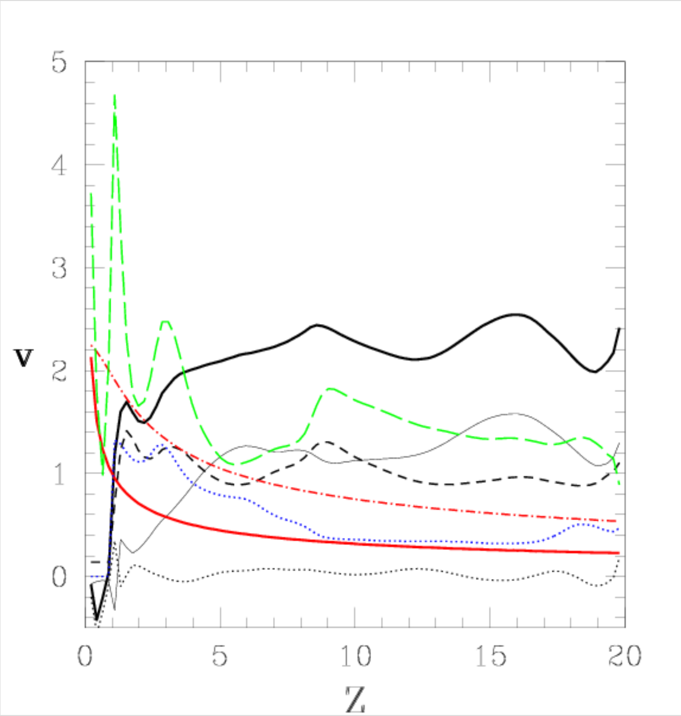
Typical solution in purely resistive simulations.

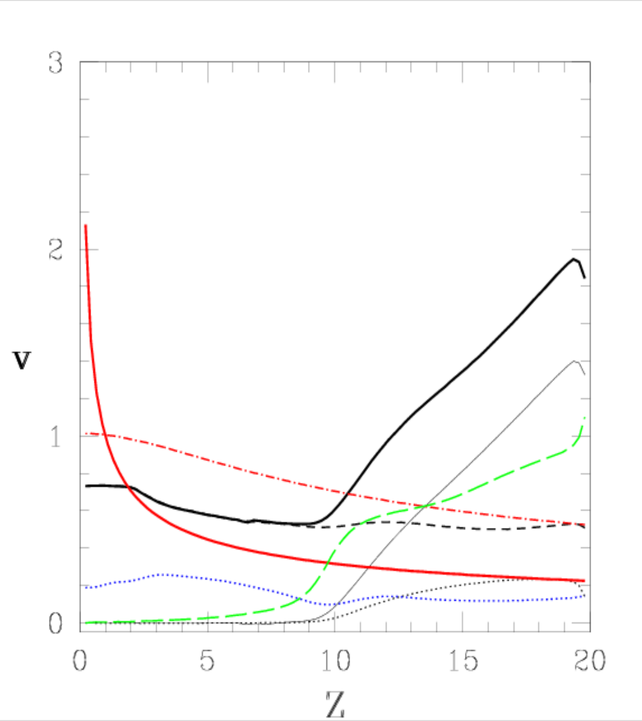
Time evolution in solutions with accretion column onto the star



- Results in simulations when accretion flow onto the star is present, together with outflows from the innermost magnetosphere.

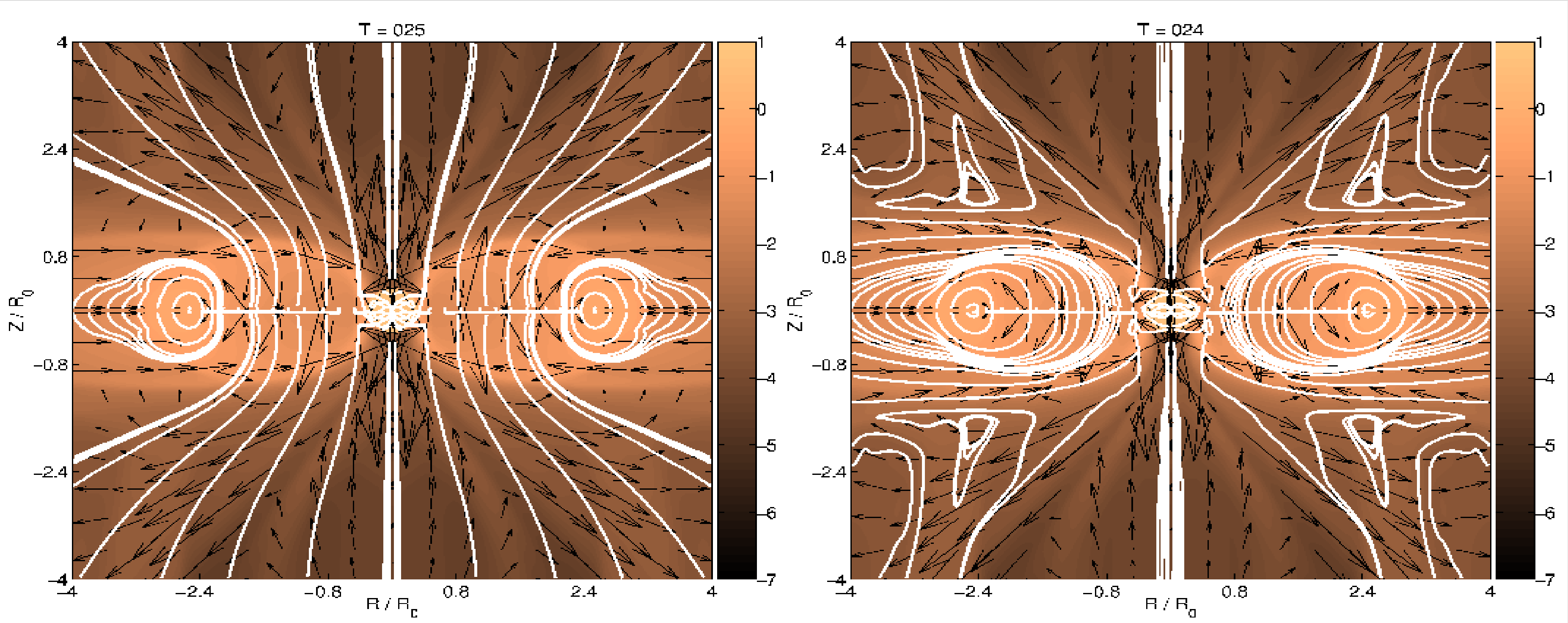
Time evolution in solutions with accretion column onto the star-velocities





- Velocity components along the axial outflow. Left: at R=1, and Right: along the conical outflow at R=5. In black lines are shown Z,R and toroidal components in thin solid, dotted and short dashed lines, and total velocity in solid thick line. Thick red line is Keplerian, and dashed green line is Alfven velocity. Red dot-dash line is the escape velocity, and dotted blue line shows the sound speed.

Effect of resistivity and 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 large differences.

Reconnection of magnetic field

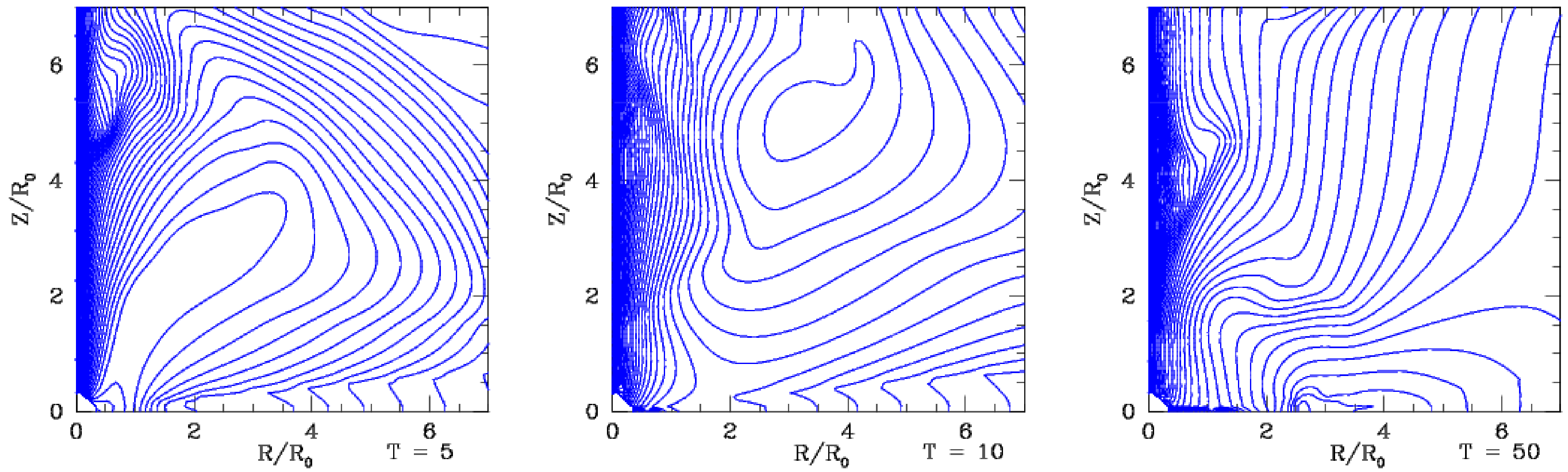
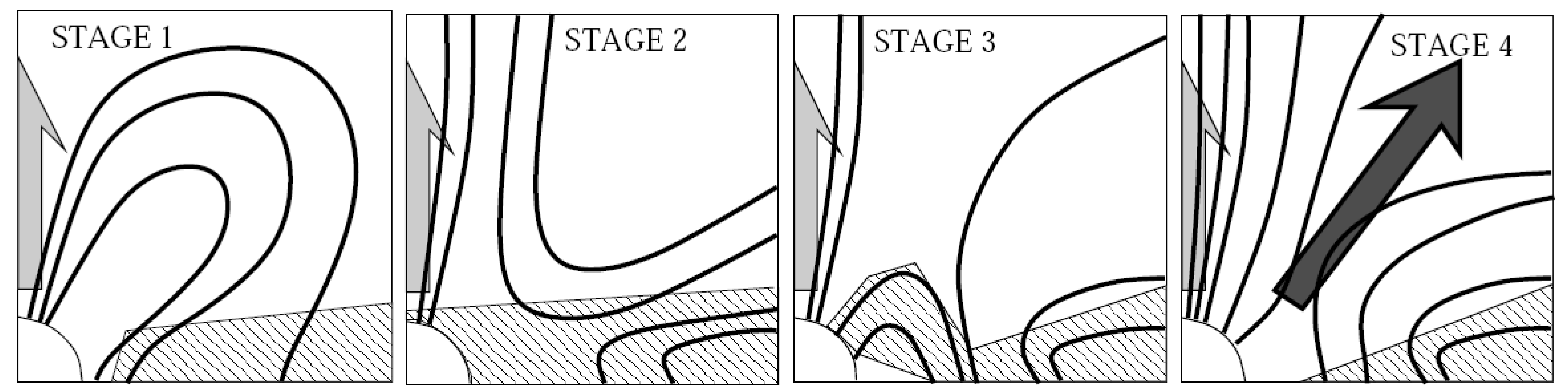


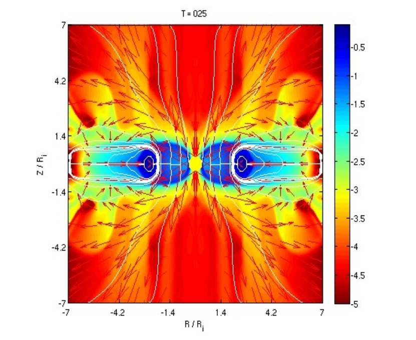
FIG. 12.— The reconnection of magnetic field in our typical solution. Shown are the poloidal magnetic field lines in different timesteps. The initial stellar dipole is pinched by the infalling matter (*Left panel*) and, with help of dissipative processes, which is resistivity in this case, through the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

- Evolution depends on reconnection, as it is necessary for reshaping of magnetic field. Resistivity facilitates reconnection, so that in effect result depends on resistivity in the magnetosphere.

Geometry of magnetic field: 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.



Summary

- Simulations show that some version of magnetospheric accretion-ejection mechanism can launch protostellar outflows and jets.
- We show that resistive simulations alone, without viscosity included, are sufficient for obtaining outflows, even when accretion column onto the star is still present. This could mean that reconnection is even more important for launching of jets than we usually consider, because it would affect the model for resistivity.
- Dissipations help to stabilize the outflow. Probably the best combination is to have both, resistivity and viscosity included in simulations. Then, models for both of them will define how much physics we learn from our simulations.