

Reconnection in magnetospheric launching of protostellar outflows



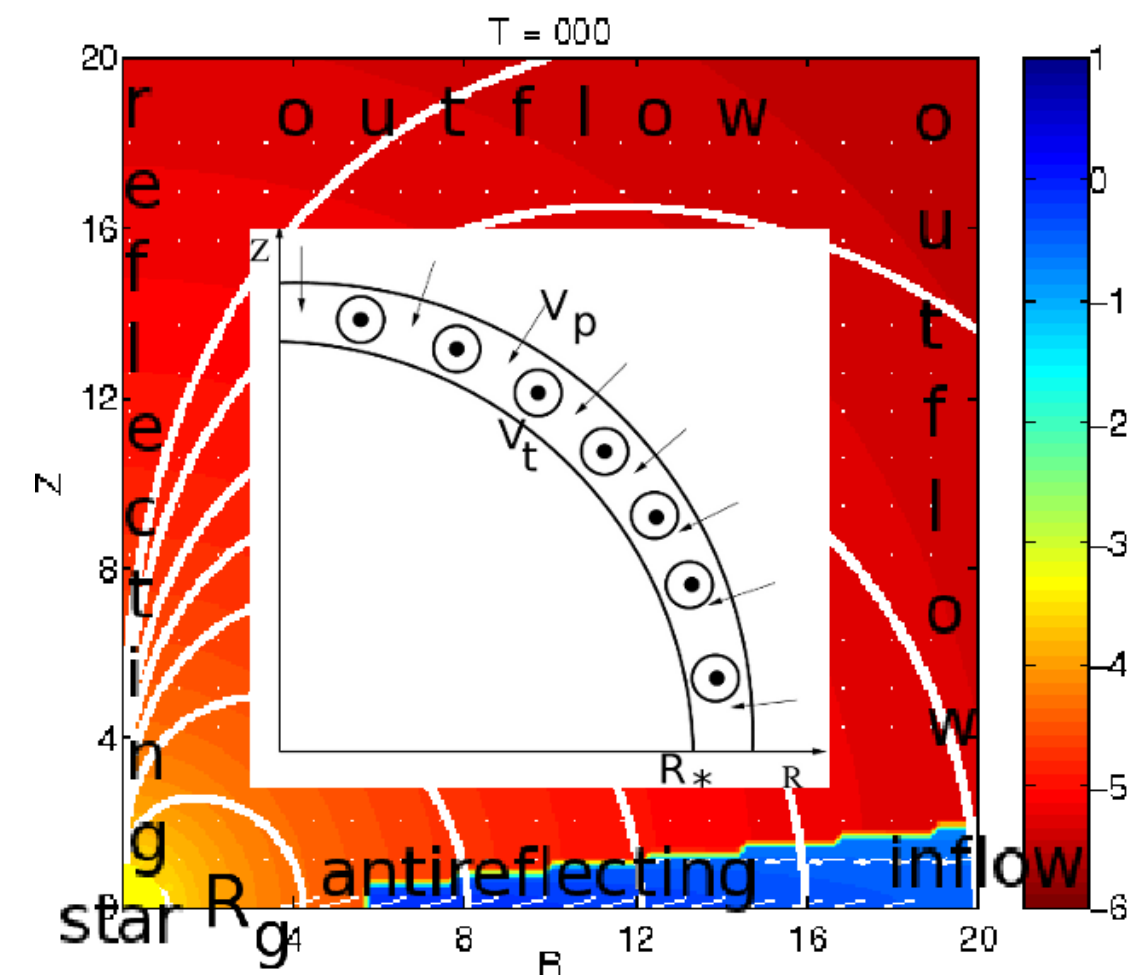
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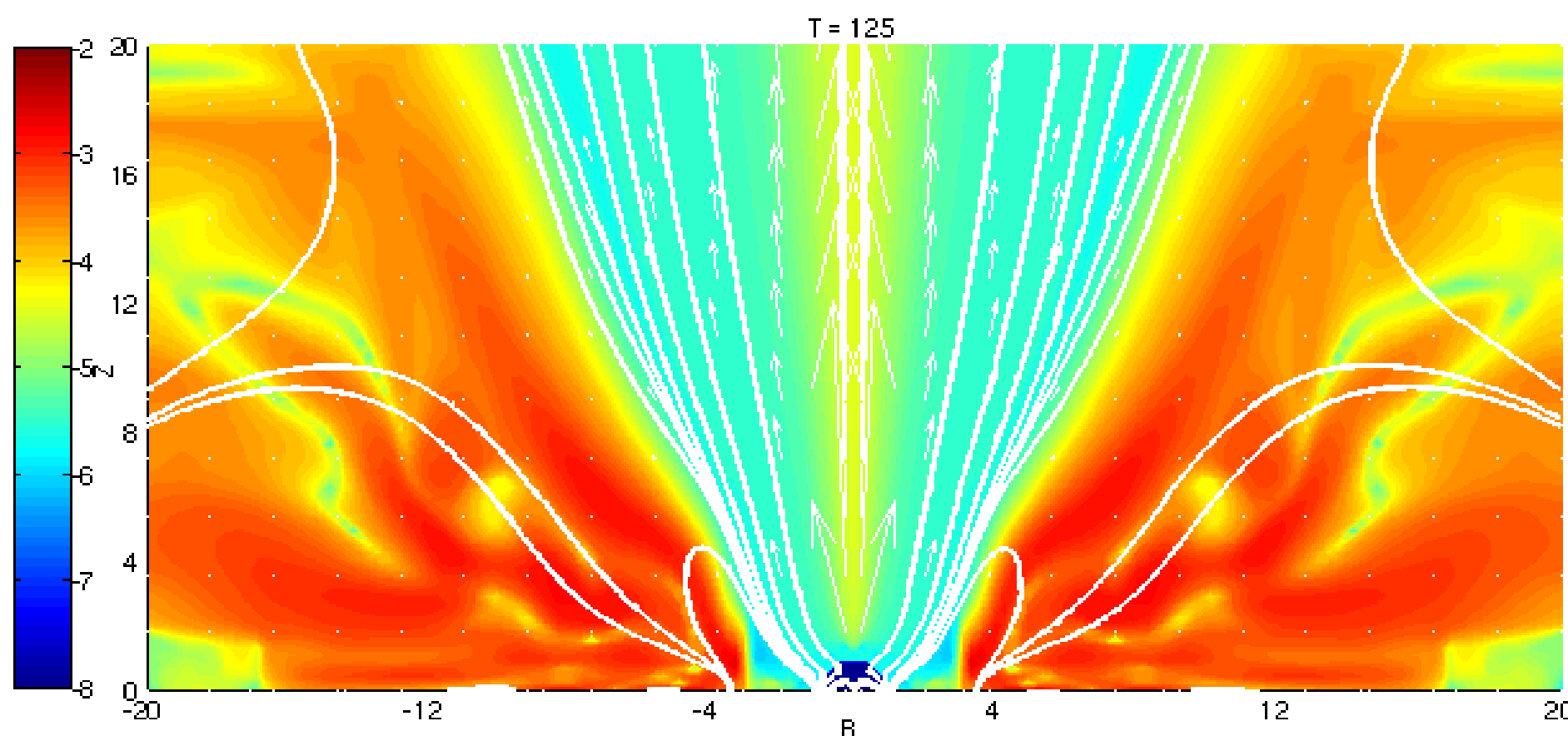


We perform resistive MHD numerical simulations with stellar dipole as an initial condition. Electrical resistivity facilitates reconnection, so that the dipole can re-shape into the stellar and disk components. This reorganization then provides channels for launching of outflows from the close vicinity of a star.

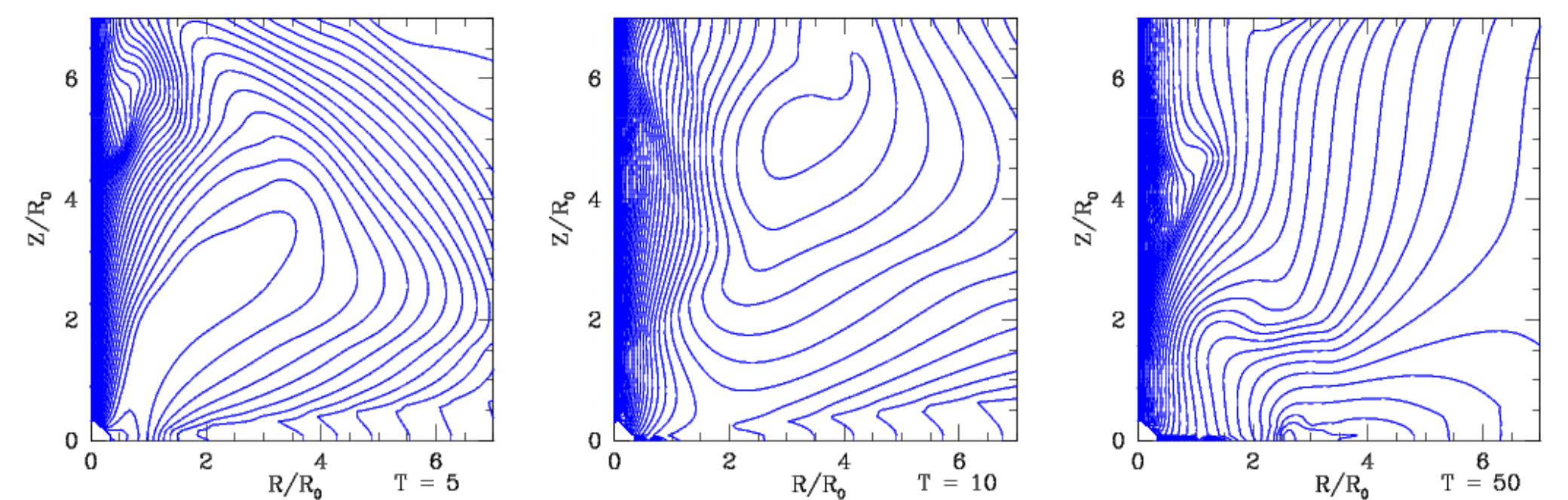
Initial and boundary conditions We set innermost region of a star-disk system, with $R \times Z = (90 \times 90)$ grid cells $= 0.2 \times 0.2$ AU. Disk is initially in a slightly sub-Keplerian rotation, with a rotating, hydrostatic corona and dipole magnetic field centred at the origin. An anomalously high resistivity is set constant nearby the equatorial plane, and higher in corona and disk it is set as function of density, $\eta \sim \rho^{1/3}$. In both cases it is for a few orders of magnitude larger than the microscopic value. We assume it is of turbulent origin. The resistive MHD equations we solve with our resistive version of the ZEUS-3D code in 2D axisymmetry option.



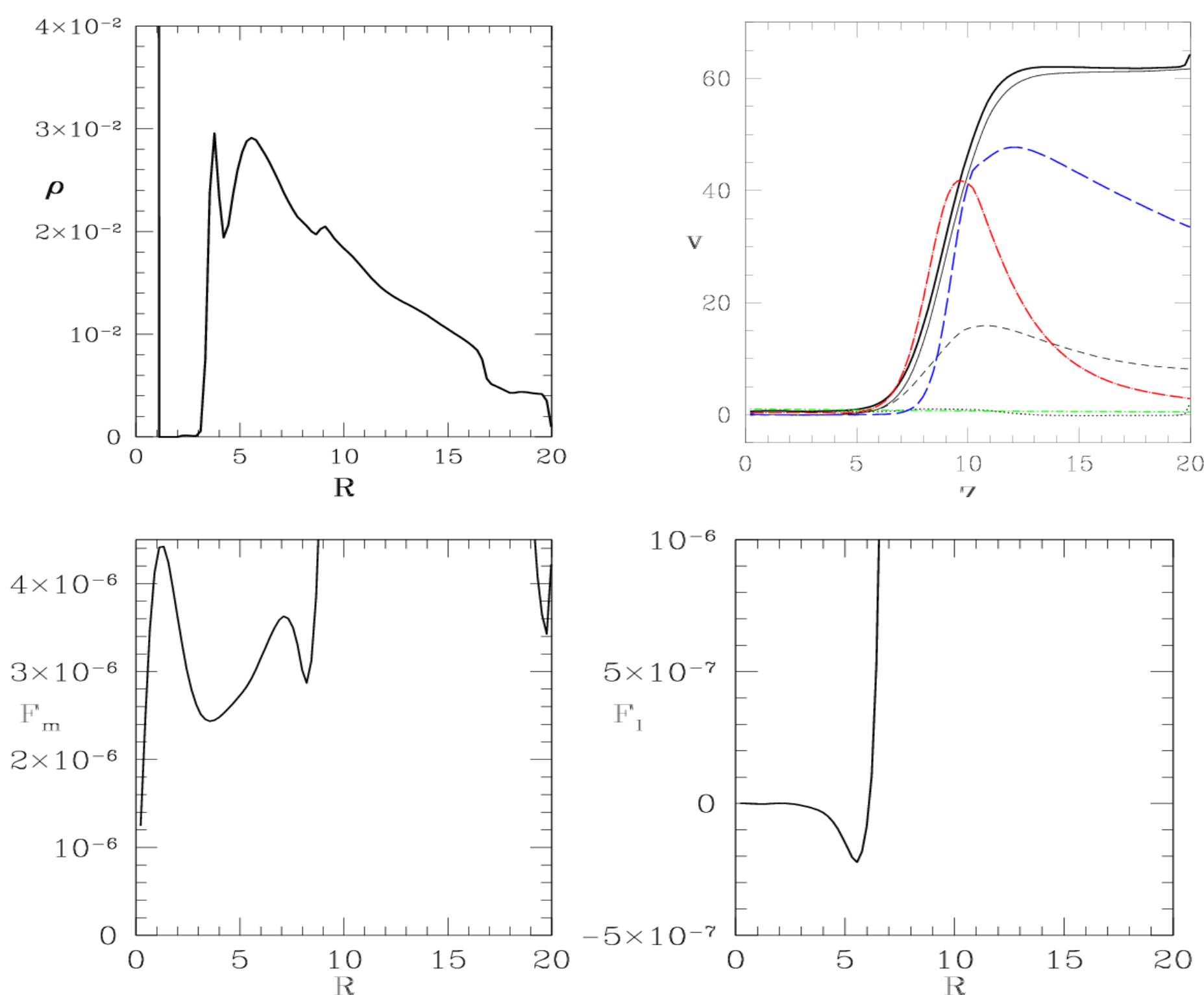
Setup of initial and boundary conditions, with inserted panel showing magnification of stellar surface in sketch drawing. In logarithmic color grading is shown the density, solid lines show the poloidal magnetic field of a stellar dipole, and vectors the velocity. Along the axis of symmetry and the disk equatorial plane, appropriate reflecting conditions are imposed. Outer boundaries are defined as open, except for a disk outer boundary, where inflow into the disk is defined, to mimic accretion from the part of the disk outside the domain. Star is set as a rotating absorbing boundary condition (with a constant rotation rate) inside the computational box, enclosing the origin.



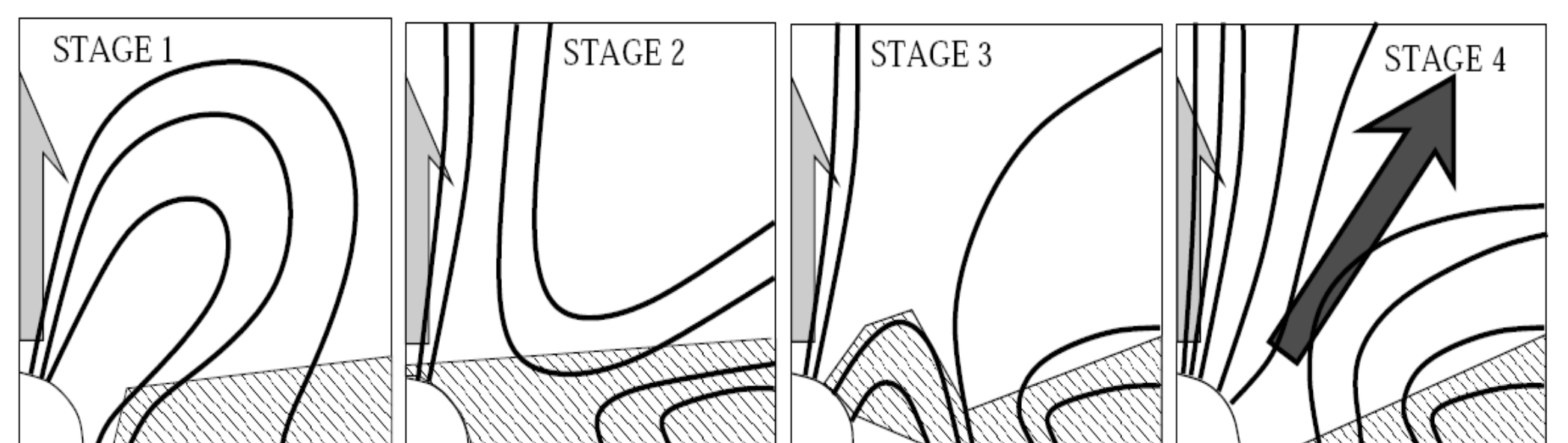
Snapshot from the simulation where reconnection takes place. In logarithmic color grading is shown the poloidal mass flux, the solid lines show poloidal magnetic field lines, and arrows show poloidal velocity vectors. The magnetic field is of the order of 100 G. Ongoing reconnection, visible here nearby $(R, Z) = (4, 4)$ helps in launching the outflows. Mass flux in our simulation is still for few orders of magnitude smaller than in the observed outflows. This could mean that additional physics should be included in the simulation.



Poloidal magnetic field lines for the different timesteps. Initial stages in the simulation are related to the reshaping of the magnetic field, because of reconnection. In our simulations resistivity facilitates reconnection, so that in effect result depends on resistivity in the magnetosphere.



Some physical quantities in our simulation, at $T=125$. Left top panel shows the density along the disk equator, and right top panel shows the velocity components along the outflow, at $R=5$, with components in Z , R and toroidal direction, and total velocity, shown in black thin solid, dotted, short dashed and thick lines, respectively. The dashed green line shows Alfvén velocity, the red dot-dash line the escape velocity, and the dotted blue line shows the sound speed. Bottom panels show the mass and angular momentum fluxes in Z direction, with focus on the flux in the outflow, up to $1/3 R_{\text{max}}$.



All simulations of star-disk interaction in our setup go through four stages: 1) relaxation with pinching of magnetic field inwards, 2) reconnection and opening of the stellar dipole, 3) narrowing of the disk gap with formation of transient funnel flow onto the stellar surface, 4) final stage of equilibrium of magnetic and disk ram pressure, with ongoing reconnection along the neutral line, with two low-mass outflows, one axial and another conical. The first two stages are related to relaxation from the initial conditions, and the last two can repeat many times during the simulation, if the quasi-stationary state is not reached.

Conclusions: Reconnection enables reshaping of magnetic field in our simulation. It is essential during the relaxation from initial conditions, for opening of the stellar dipole, and later in the simulation as a part of the launching mechanism.