Resistive MHD numerical simulations of outflows in star formation. Role of reconnection.

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Outline

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  -Reconnection in astrophysics
- Models of reconnection
- Numerical simulations of Petchek reconnection
- Magnetospheric interactions in star-disk simulations
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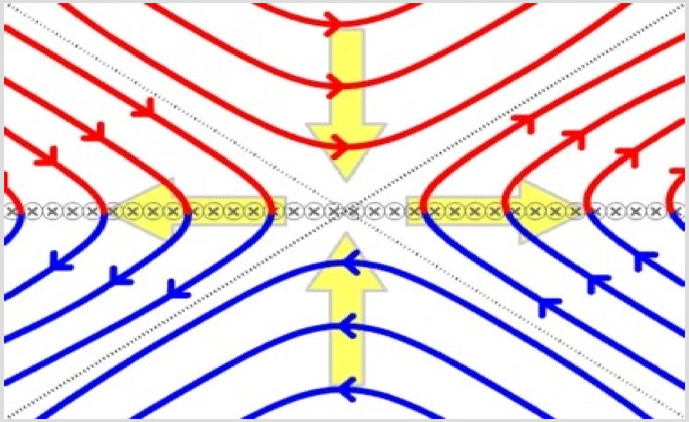
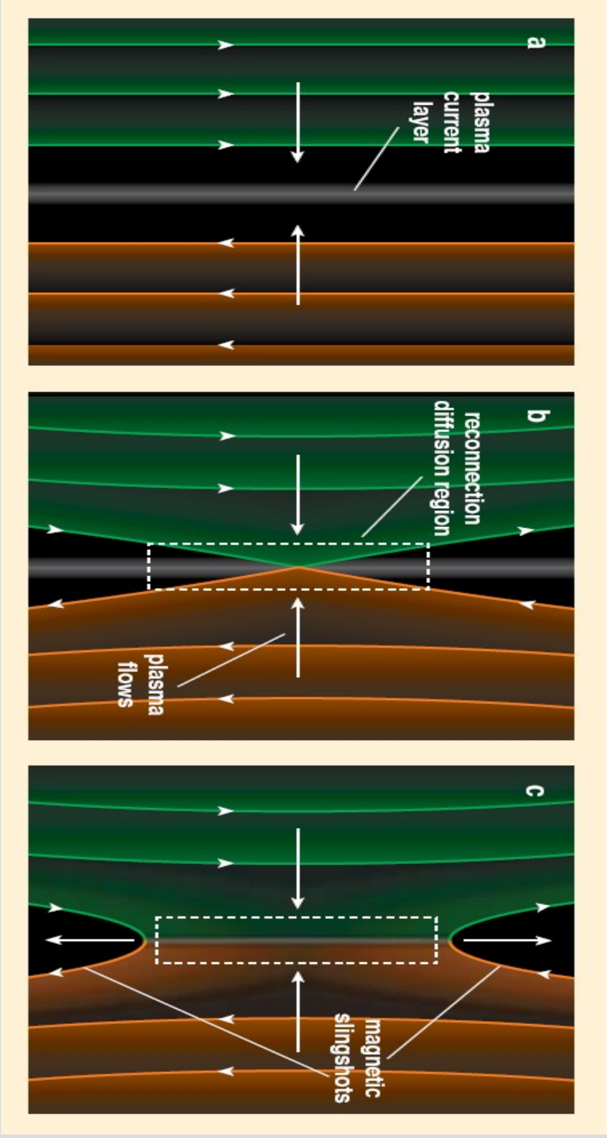
Physical picture-basic

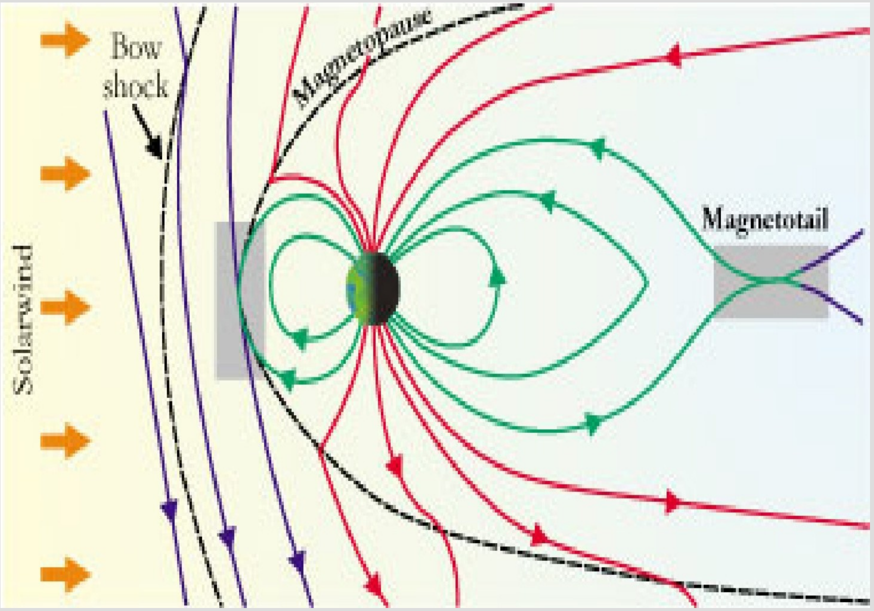
- Magnetic reconnection: process in which magnetic field lines change connection with respect to the sources.
- In effect, magnetic energy is converted into kinetic and thermal energies, i.e. into acceleration and heating of plasma.



- Assumed to occur on different astronomical scales and in different objects, so we study it from Earth magnetosphere to solar physics and cosmology.



Reconnection in astrophysics-Earth



Main features in the problem of reconnection in the Earth magnetosphere. Shadowed boxes mark the reconnection sites. Solar wind carries interplanetary mag. Field into the geomagnetic field. Reconnection of these fields allows energy and charged particles from the solar wind to enter Earth magnetosphere. Open mag. Field lines are carried downstream in the solar wind and reconnect in the distant tail of magnetosphere.

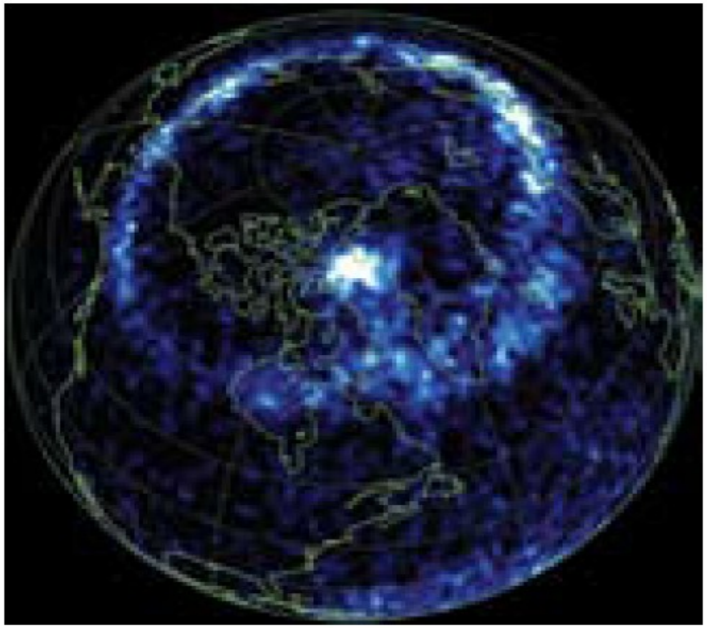


Figure 4. Auroras are usually created by electrons but this image shows a North Pole aurora emitted by protons, which glow brightly in the ultraviolet range. The nearly circular white spot results from reconnection with a northward-directed interplanetary magnetic field. (Image courtesy of the NASA IMAGE mission.)

Reconnection in astrophysics-Earth, measurements

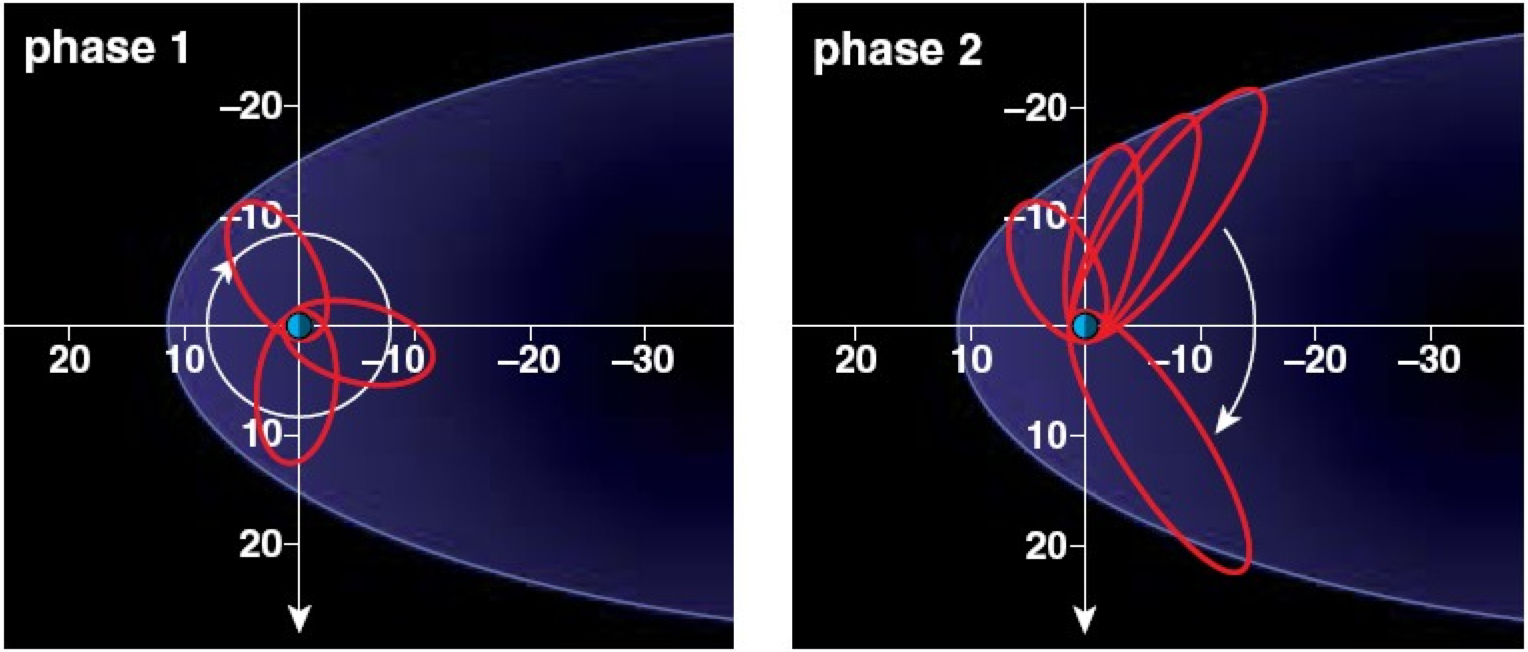
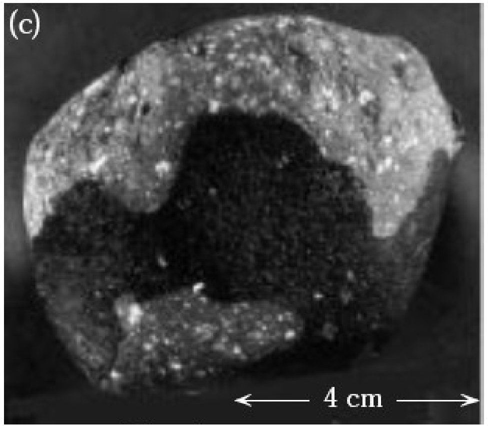
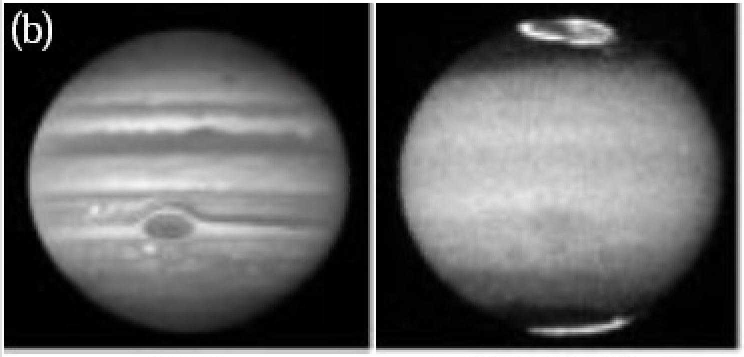


Figure 7. The Magnetospheric Multiscale mission will use a set of four satellites to probe magnetic reconnection at the boundary of the magnetosphere. The tetrahedrally aligned satellites will gradually precess their orbit in each phase of the mission over a period of many months. In phase one, at a distance of 12 Earth radii, the group will be on the day side so that the crafts hover near the boundary between the magnetosphere and the solar wind. In phase two, at a maximum distance of 25 Earth radii, the group will move to the night side, where reconnection in the tail of the Earth's magnetic field is most common.

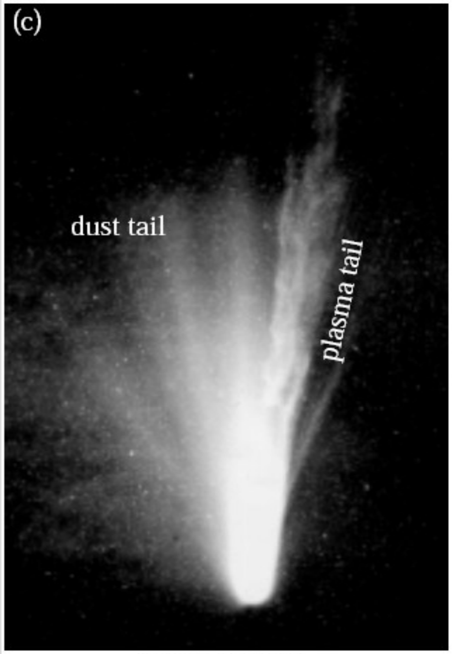
Reconnection in astrophysics-solar system



Allende meteorite



visible ultraviolet



12 April 1986

- Examples of **eventual** signatures of reconnection process in Solar system. Chondritic inclusions in metorites are thought to form in the flares in accretion disk, during the formation of the Sun.
- Jupiter shows auroras, too.
- Cometary tails divide into the dust and plasma tail, and disconnection of the plasma tail, which consists of gases of water, carbon monoxide and other simple atoms and molecules evaporated off the comet which become ionised by interaction with sunlight. The comet ion tail responds as a sort of "wind sock", that gets deflected in the direction of the outflowing solar wind. If the interplanetary magnetic field and solar wind are disturbed, reconnection effect will become quite visible, most likely as a rippling in the ion tail, or the tail can be even torn away off the comet.

Reconnection in astrophysics-Sun

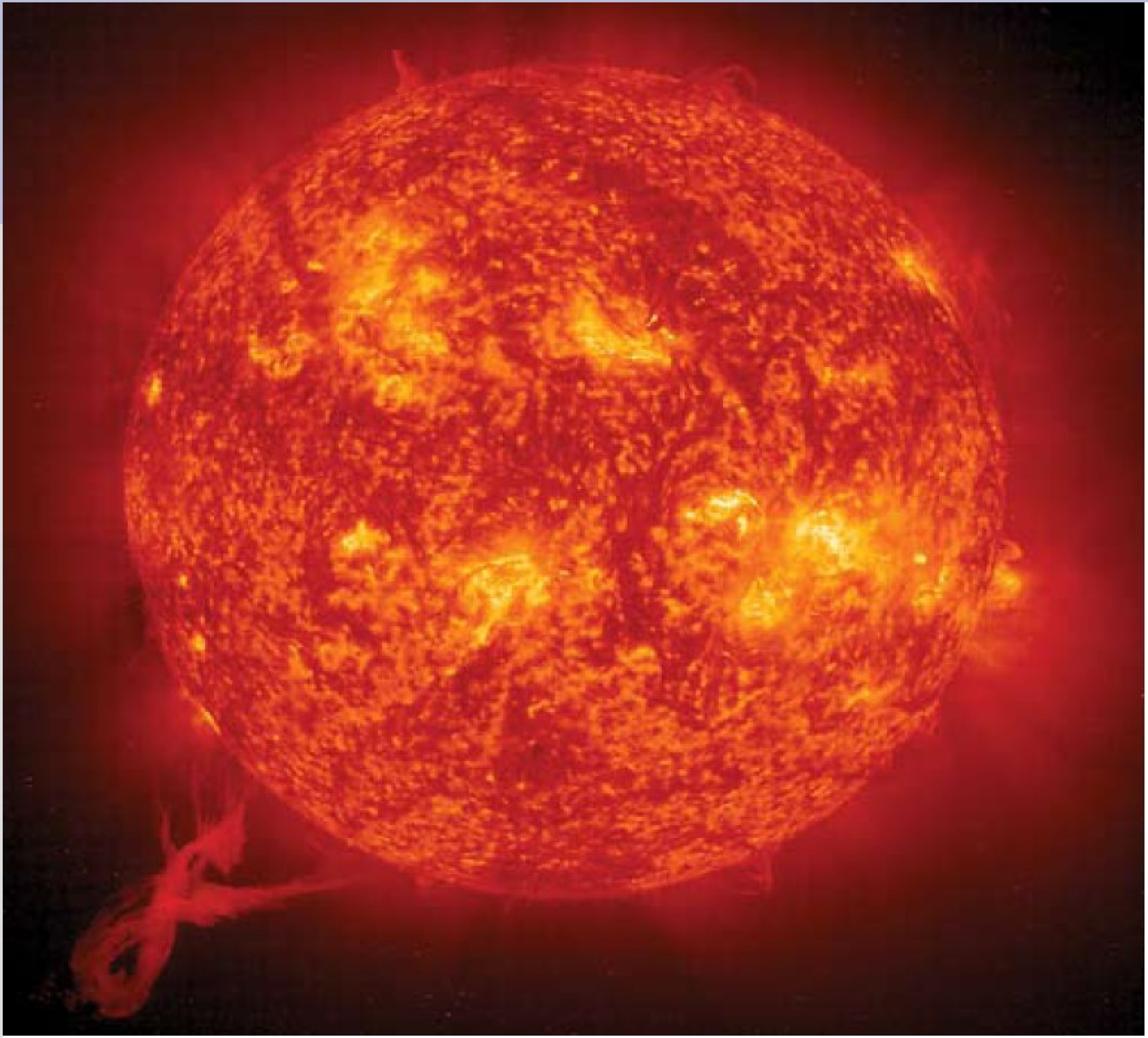


Figure 1. Extending over many thousands of kilometers and with a mass of more than 100 billion tonnes, a twisting solar prominence protrudes out of the Sun's corona in the bottom left of this image. Magnetic fields are heavily involved in the formation of these and other solar features, such as flares and coronal mass ejections. When these fields break apart and link up with each other, in a process called magnetic reconnection, such solar features can explosively release energy that can have consequences on Earth. (Image is courtesy of SOHO/ESA and NASA.)

Reconnection in astrophysics-solar flare

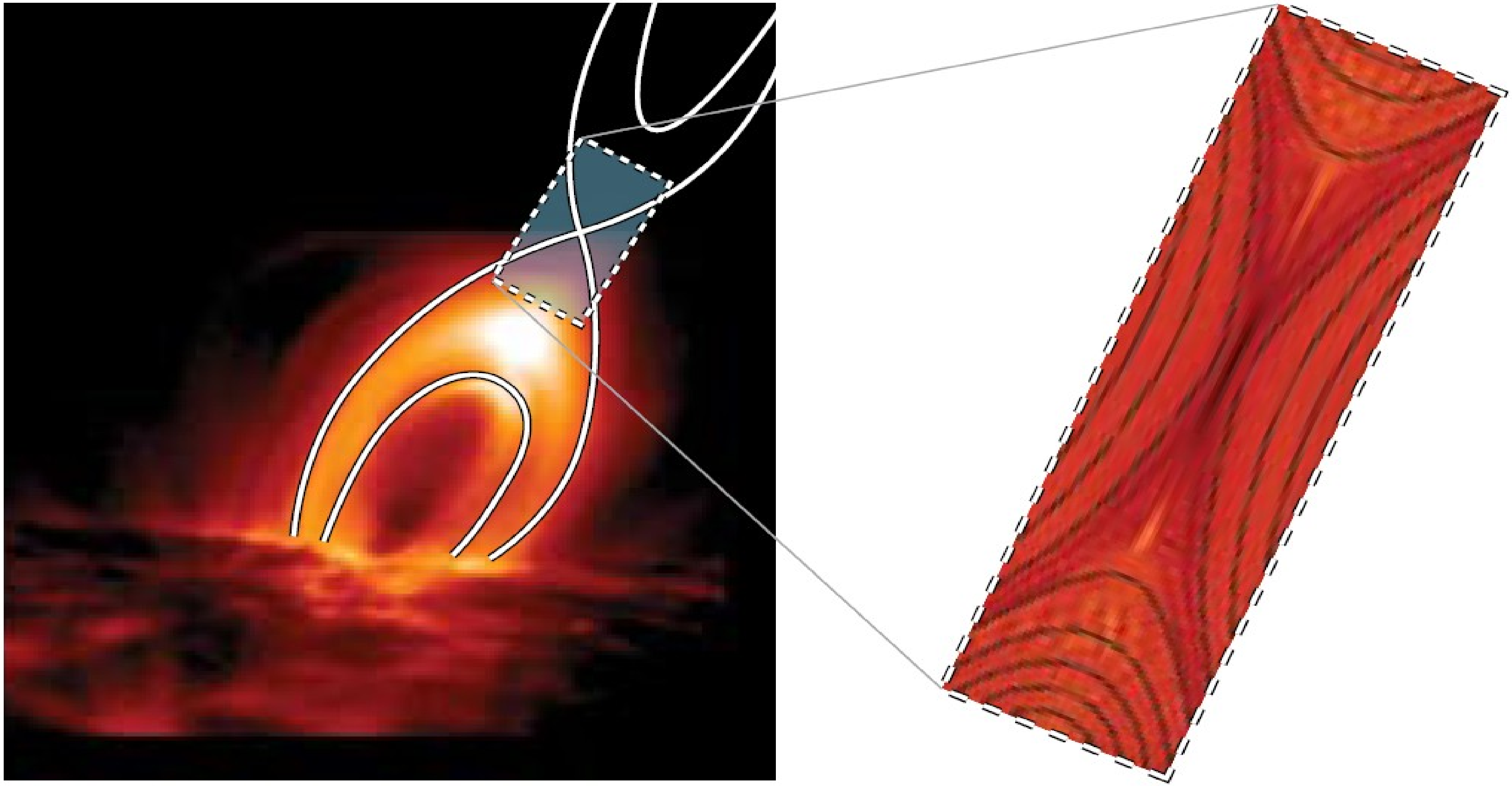


Figure 2. An x-ray image of a solar coronal structure from Japan's Hinode spacecraft *(left)* is overlaid with an illustration of the magnetic field lines and the reconnection region *(dotted box)* that produces it. Computer simulations of electron populations in reconnection regions *(right)* have been key in deciphering more about how this event unfolds. (Left image is courtesy of the Japanese Space Agency, right image is courtesy of James Drake and Michael Shay, University of Delaware.)

Reconnection in astrophysics-Sag A

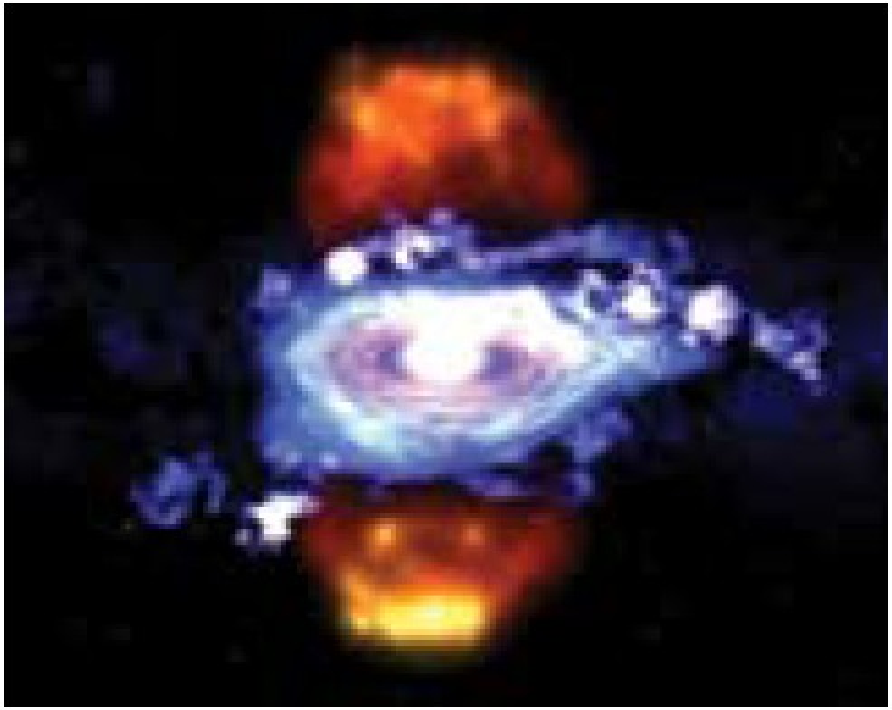


Figure 5. The supermassive black hole Sagittarius A and its accretion disk have been observed to emit massive flare ejections, which may be caused by magnetic reconnection. (Illustration courtesy of the NASA Compton X-ray Laboratory.)

Reconnection in astrophysics-supernovae

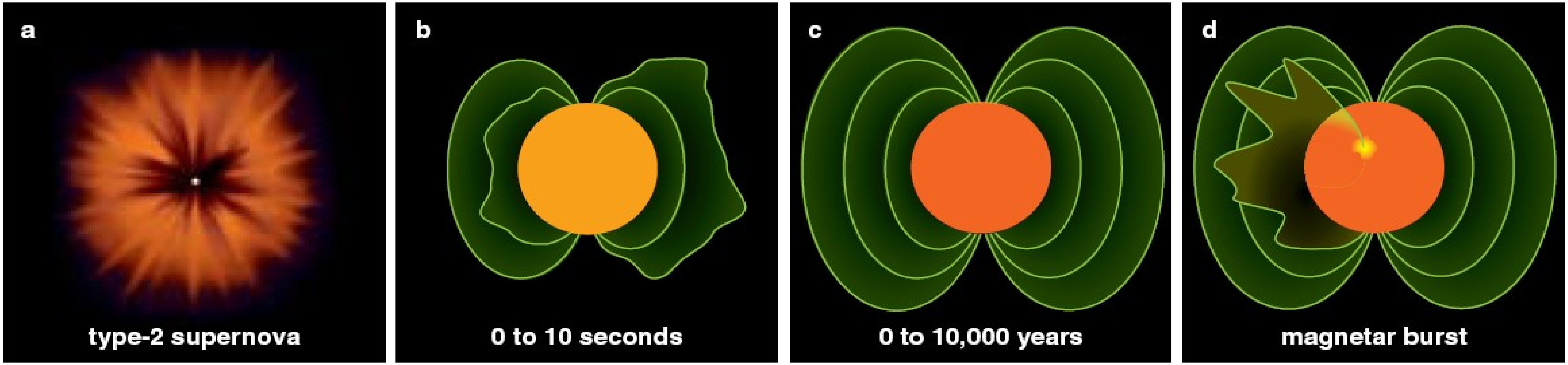
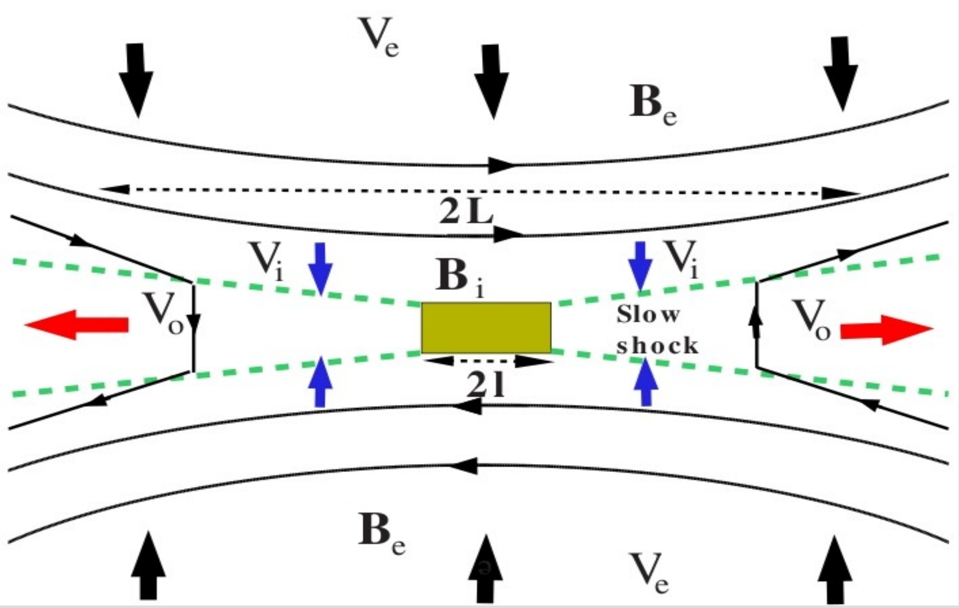


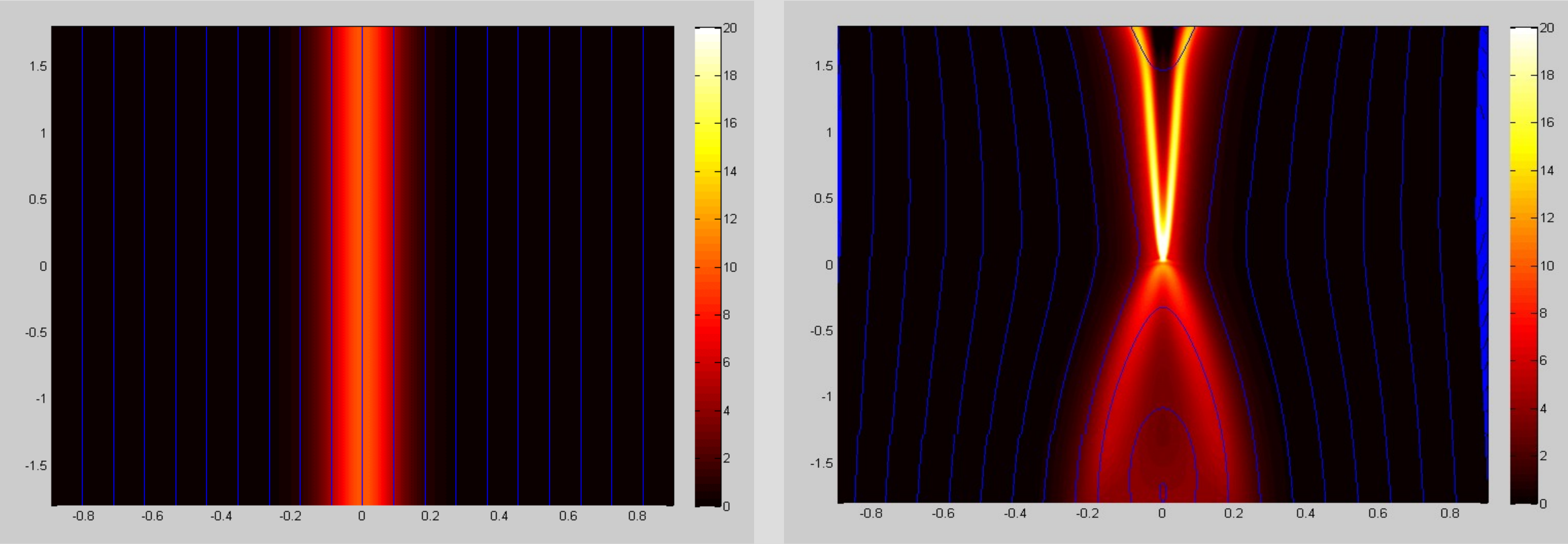
Figure 6. Massive stars die in type-2 supernova explosions; their stellar cores implode into a dense ball of subatomic particles *(a)*. If the newly formed neutron star is spinning fast enough, it will generate an intense magnetic field, and field lines inside the star will become twisted from the rapid movement *(b)*. Over the first 10,000 years of its life, the star will settle down so that there are turbulent fields inside but smooth field lines on the surface *(c)*. At some point these internal stresses crack the solid surface, resulting in a quake that creates an electrical current burst and a flow of material that emits x rays *(d)*. The material dissipates in a matter of minutes.

Model of reconnection



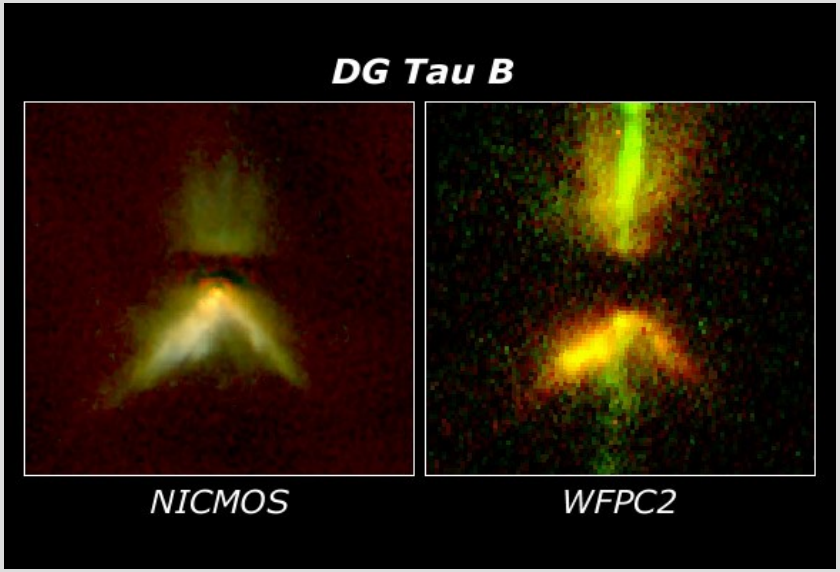
Petschek reconnection (1964) was the first model for fast reconnection. The first, simplest and robust model of reconnection was the Sweet-Parker model, which looks similar, but with where reconnection happens within a thin current sheet, separating two large volumes containing uniform, very different magnetic fields. Problem is that the reconnection speed in this model is too slow for typical astrophysical conditions, as it is determined by the large scale geometry of the problem. Therefore, alternative models that allow fast reconnection have been investigated. Two kinds of scheme for fast reconnection have been proposed: those which modify the microscopic resistivity, resulting in wider current sheet, and those that change the geometry, in effect reducing the characteristic scale, as seen above.

PLUTO simulations of Petchek reconnection



Repeated results for Petchek reconnection recently obtained by Baty et al. (2009) [Phys. Of Plasmas 16, 012102], with asymmetric profile of density. Simulations by PLUTO code, done by IAA Summer student, Huang, Ruei-Yang. Shown are current densities. For symmetric density profile, there is no reconnection. We continue this research with anisotropic resistivity, to eventually find model which could be used in star-disk simulations. This goes to topic of turbulent reconnection, but it is still in investigation-see Kowal et al. 2011.

Young stellar objects-observations



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

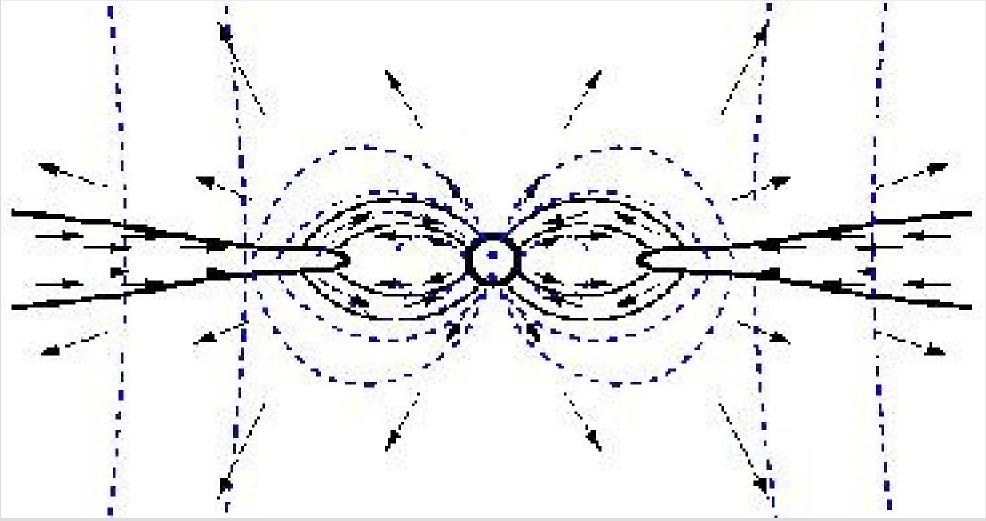
HST-NICMOS camera image of IRAS 04302+2247. Central object is hidden from direct view and seen only by the nebula it illuminates. Disk of dust and gas appears as the thick, dark band crossing the centre of the image. The disk has a diameter of 15 times the diameter of Neptune's orbit, and has a mass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

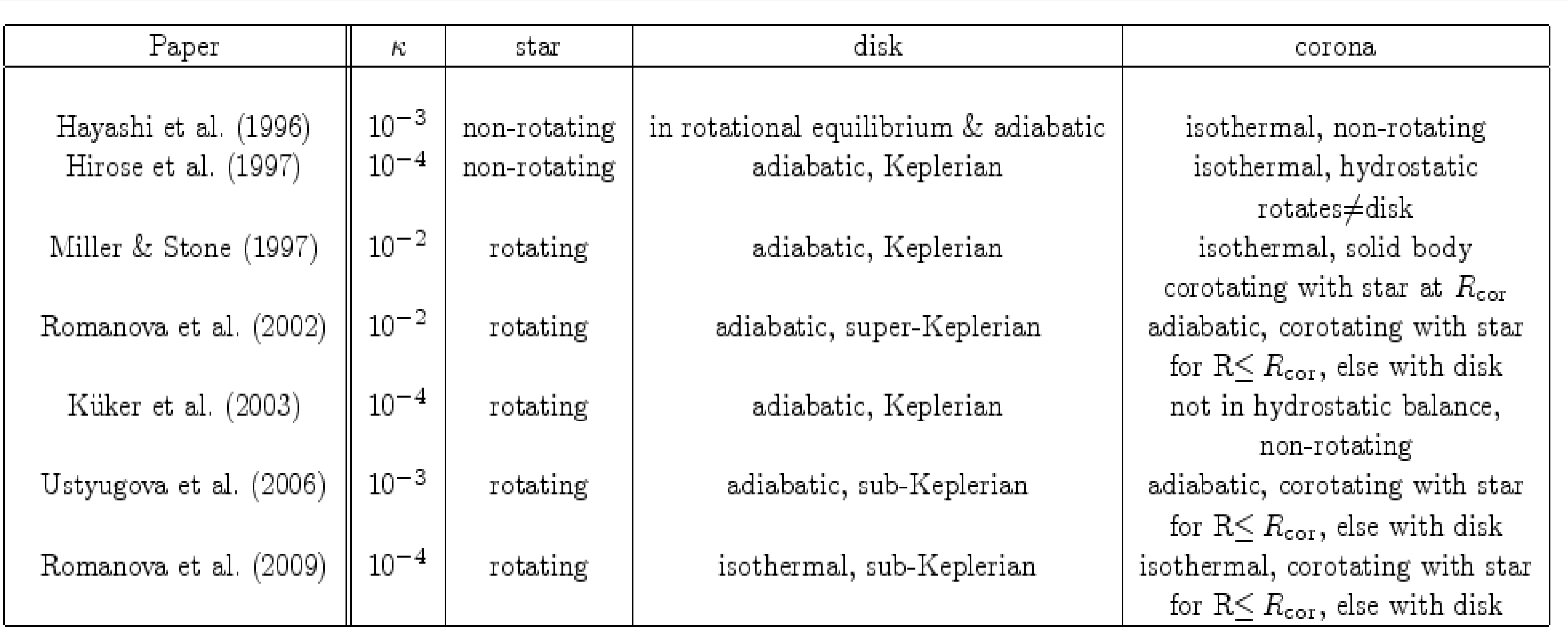
- The earliest models were about stellar wind, then were models with disk wind, combination of those seems to be needed to explain observations.

- 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



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.

Our numerical simulations-setup

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

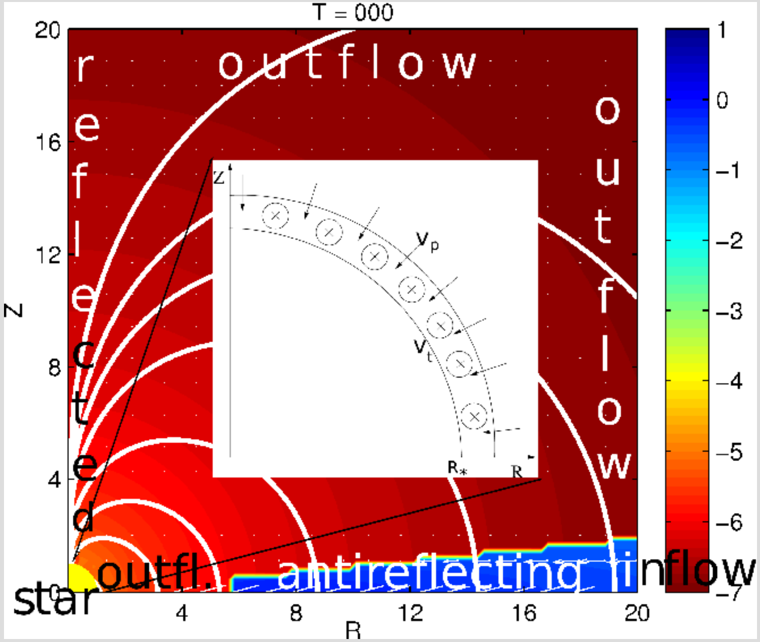
$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\, \mathbf{v} \right] + \nabla p + \rho \nabla \Phi - \frac{\boldsymbol{j} \times \boldsymbol{B}}{c} = 0 \quad (2)$$

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

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

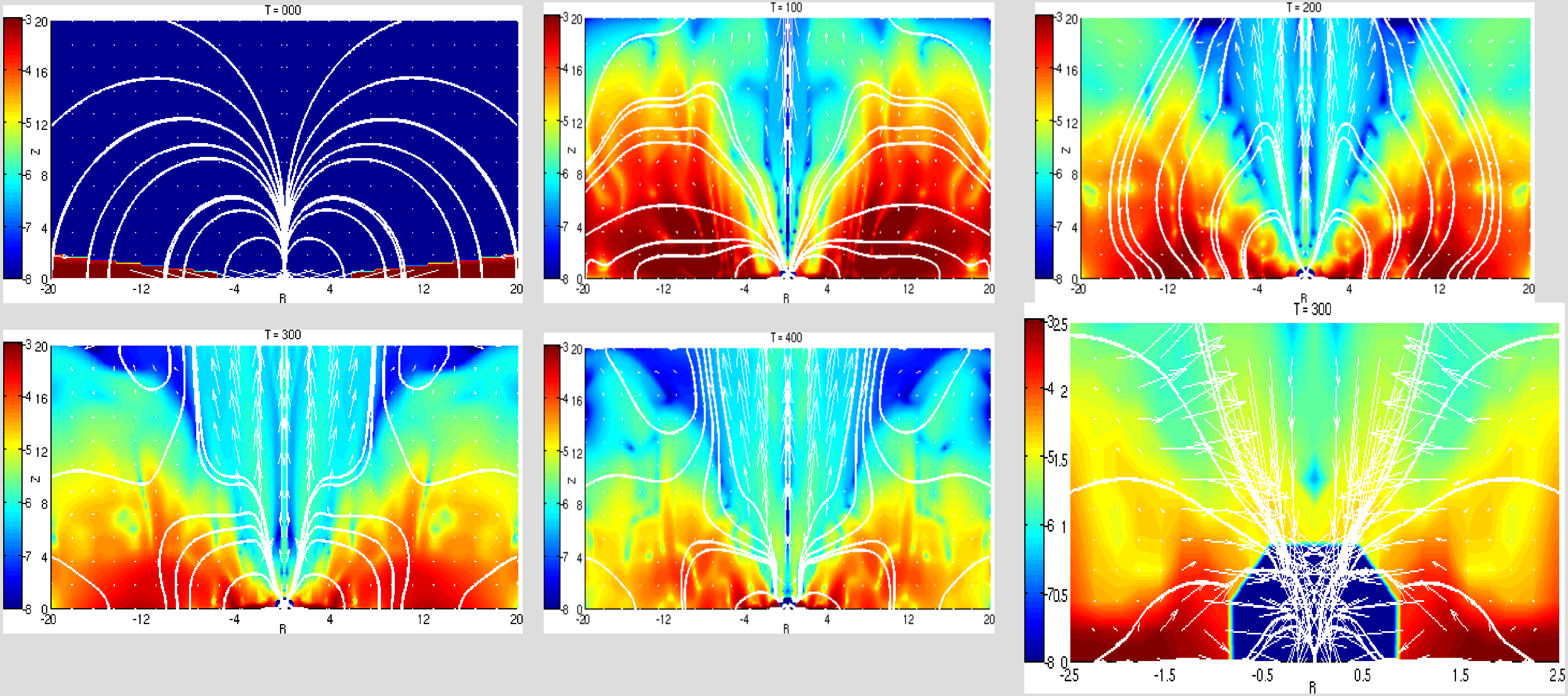
$$\boldsymbol{j} = \frac{c}{4\pi} \nabla \times \boldsymbol{B} \ . \quad (5)$$

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 $\eta = \eta_0\ \rho^{1/3}$



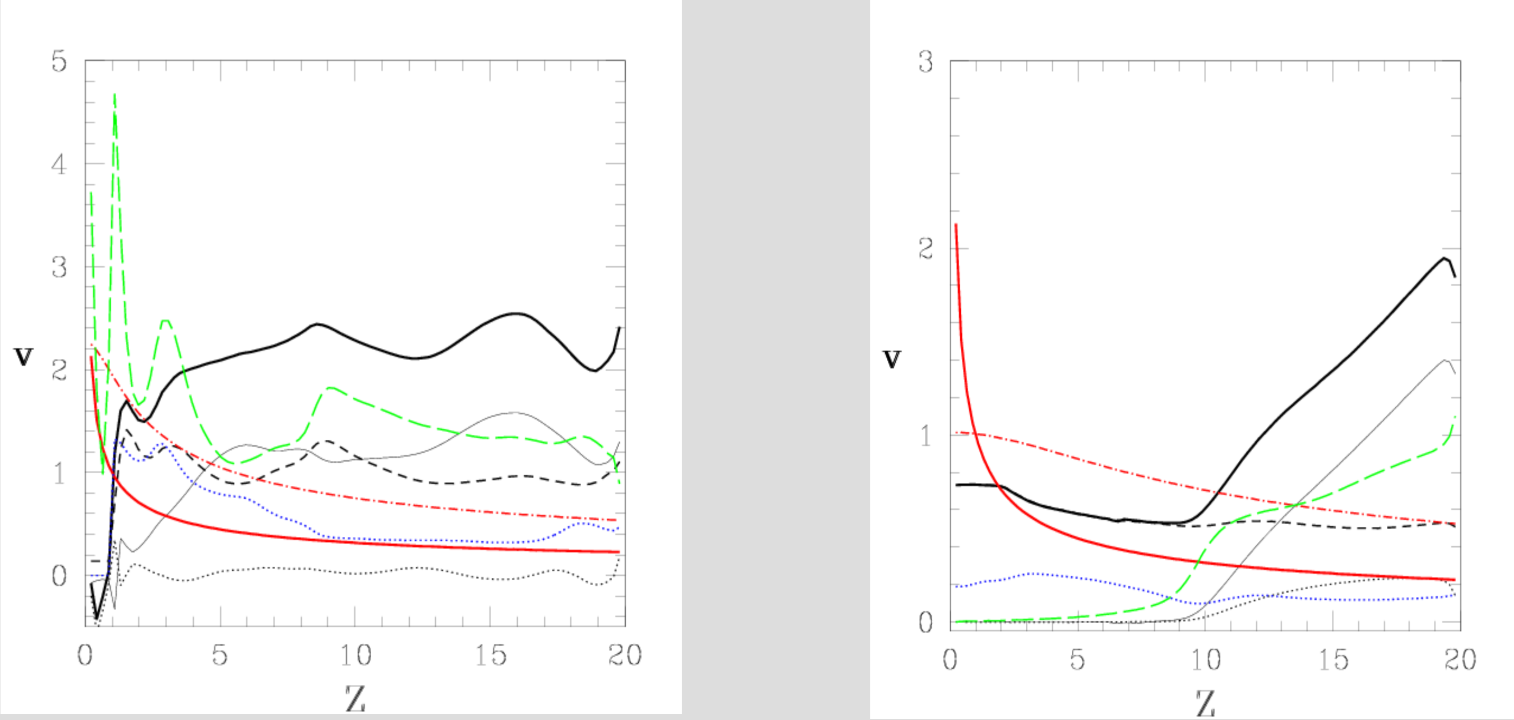
- Code Zeus347
- Innermost region of the star-disk system, RxZ=0.2x0.2 AU
- In the disk, resistivity is constant. Only artificial viscosity is included.
- Two regimes:
  -For R_cor > R_i   slow rotating star
  -For R_cor < R_i   fast rotating star

Time evolution in solutions with accretion column onto the star



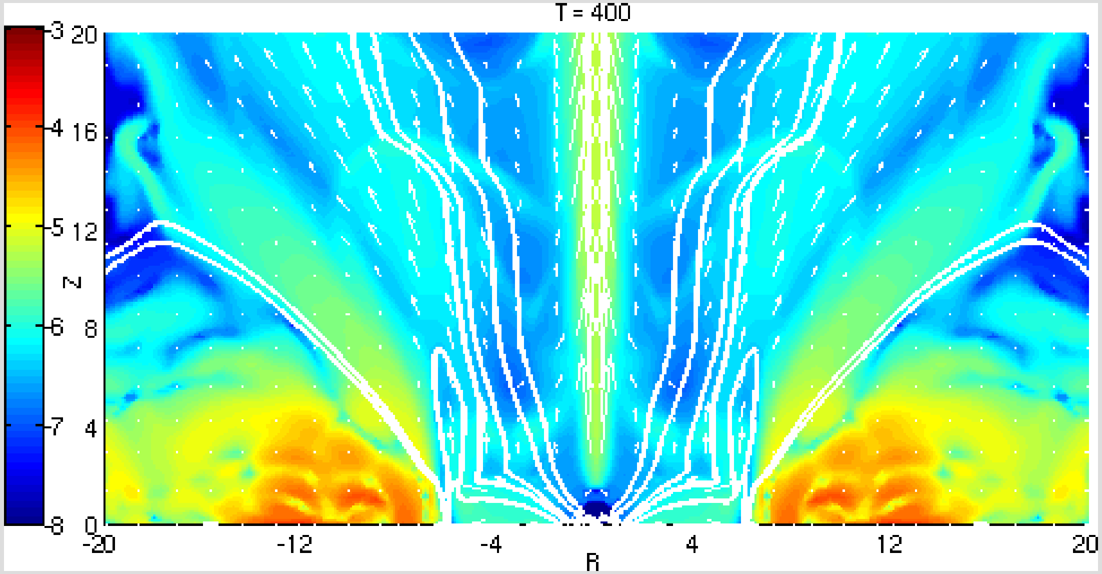
- Results in simulations when accretion flow onto the star is present, together with outflows from the innermost magnetosphere.

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



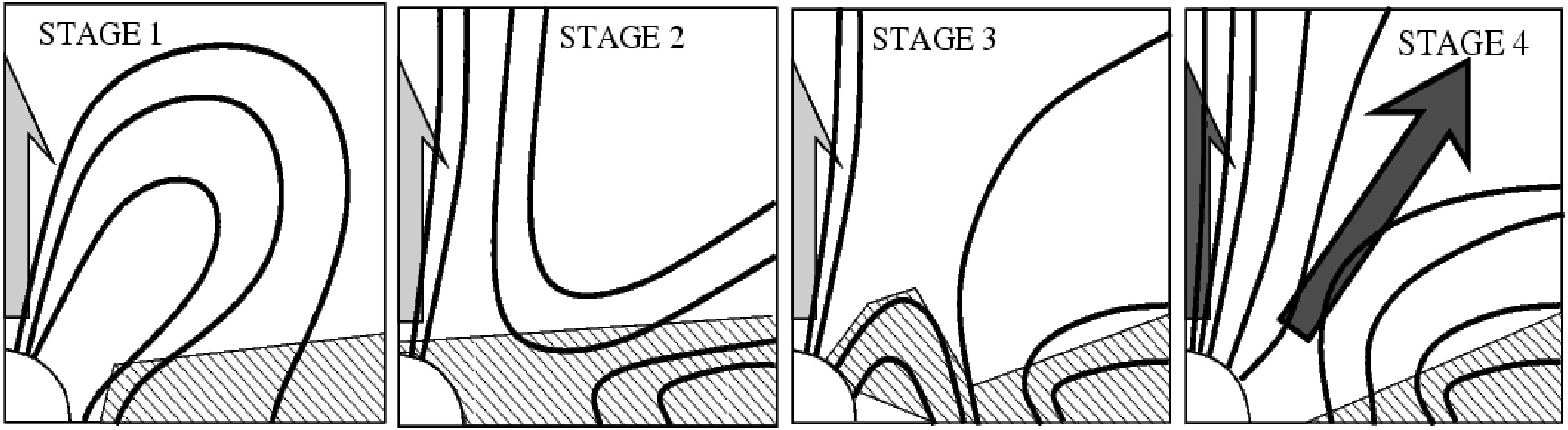
- Velocity components along the axial outflow. Left: at R=1, and Right: along the conical outflow at R=5. In black lines are shown Z,R and toroidal components in thin solid, dotted and short dashed lines, and total velocity in solid thick line. Thick red line is Keplerian, and dashed green line is Alfven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

Solutions without the accretion column onto the star



Result in the same setup, for portion of a parameter space where stellar rotation is four times slower. There is no accretion columns onto the star, but outflows, now with different fluxes and opening angle of conical outflow, are still present.

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.

Reconnection of magnetic field

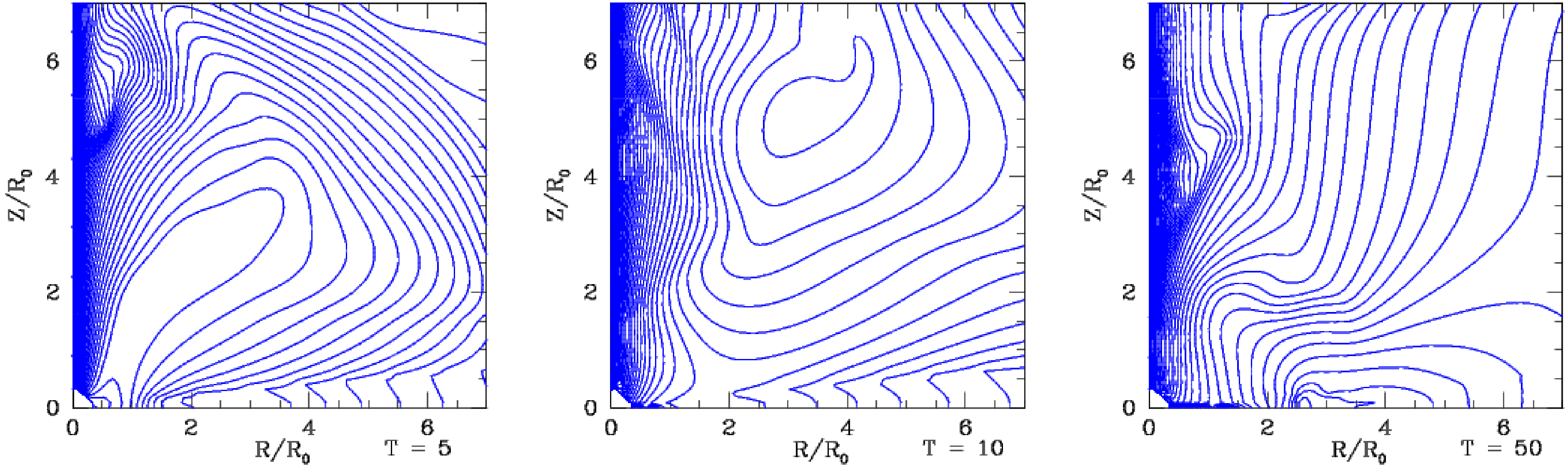
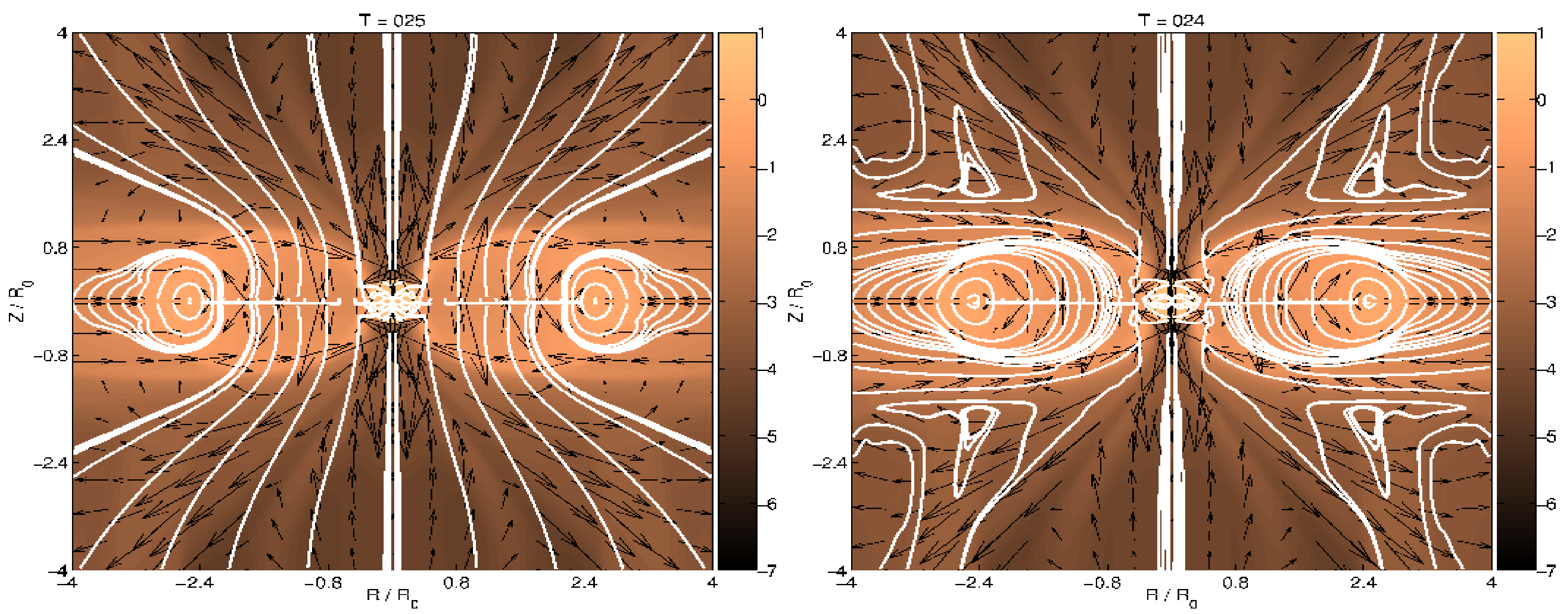


FIG. 12.— The reconnection of magnetic field in our typical solution. Shown are the poloidal magnetic field lines in different timesteps. The initial stellar dipole is pinched by the infalling matter (*Left panel*) and, with help of dissipative processes, which is resistivity in this case, through the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

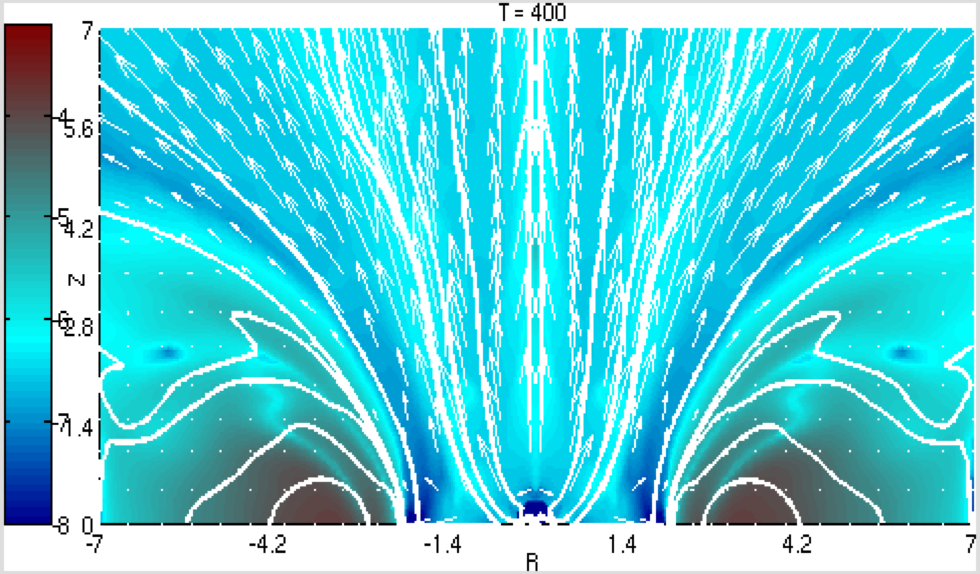
- The first three stages are related to the reshaping of the magnetic field, because of reconnection. Resistivity facilitates reconnection, so that in effect result depends on resistivity in the magnetosphere.

Effect of reconnection on solutions

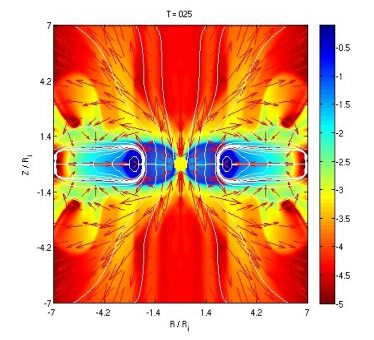


- *Left* is the solution with resistivity in magnetosphere included, R*ight* is without resistivity. The density (color grading) is almost identical in both cases , but magnetic field geometry (solid lines) shows big difference.

Another dissipation process: (artificial) viscosity



- Portion of parameter space with Pr=viscosity/resistivity >1.
- Similar results; viscosity helps to stabilize the outflow.
- Mass and angular momentum fluxes increase with larger magnetic field. Angular momentum increases with larger viscosity.



Summary

- Reconnection is one of crucial physical processes in the astrophysical plasmas.
- 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 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 enter in the model for resistivity.
- Viscosity helps to stabilize the outflow. Probably the best combination is to have both, resistivity and viscosity included in simulations.