Disk–Star Magnetic Coupling

Basic concepts

Spherical accretion with $\dot{M}_{\rm in} = 4\pi R^2 \rho(R)|V_R(R)|$ at free-fall speed $V_{\rm ff}(R) = (2GM_*/R)^{1/2}$ onto a star of mass M_* will be stopped by the magnetic stresses of the stellar dipolar field at the distance where the ram pressure of the flow ($\rho V_{\rm ff}^2$) becomes comparable to the magnetic pressure of the stellar field ($B^2/8\pi$).

For accretion in the equatorial plane, $B(r) = \mu_*/r^3 = B_* R_*^3/r^3$, and one obtains the nominal Alfvén radius

$$r_{\rm A} = \frac{\mu_*^{4/7}}{(2GM_*)^{1/7}\dot{M}_{\rm in}^{2/7}} \, . \qquad (47)$$

Although the radial ram pressure of the flow is relatively small for disk accretion, one can define in that case a magnetospheric boundary radius $r_{\rm m}$ with a similar parameter dependence from the requirement that the total material and magnetic stresses (or energy densities) be comparable, $\rho V_\phi^2 + P = B^2/8\pi$.

The physical process of disk truncation requires that the torque exerted by the stellar field that penetrates the disk be comparable to the rate of angular momentum transported in by the accretion flow, $-r^2 B_\phi B_z = \dot{M}_{\rm in} d(r^2\Omega)/dr$. Taking $|B_\phi| \sim B_z$ (the field lines will be twisted by the differential rotation in the disk until the field is strong enough to enforce its own angular velocity) and setting $|d\Omega/dr| \sim \Omega_{\rm K}/r$ yields an inner disk truncation radius that is again of the order of $r_{\rm A}$,

$$r_{\rm d} = k_{\rm A}\, r_{\rm A}\ . \qquad (48).$$

Semianalytic models (e.g., Ghosh & Lamb 1979) and numerical simulations (e.g., Long et al. 2005) give $k_{\rm A} \approx 0.5$.

If the star is rotating with angular velocity Ω_*, one can define the corotation radius by equating $\Omega_{\rm K}(r) = \Omega_*$, which gives

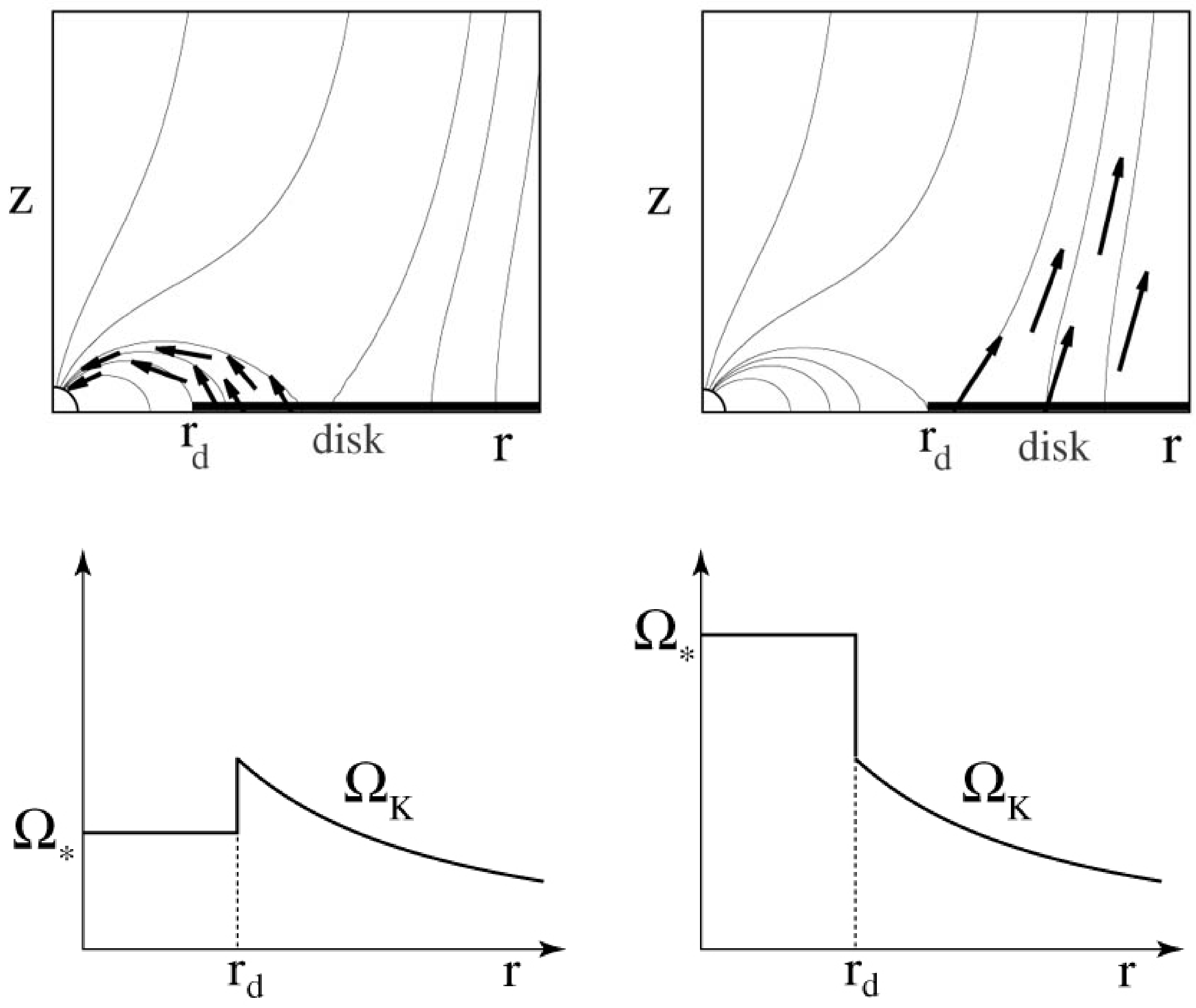
$$r_{\rm co} = (GM_*/\Omega_*^2)^{1/3}\ . \qquad (49)$$

The interaction of the disk with the stellar dipolar field naturally divides into two qualitatively different regimes depending on the ratio $r_{\rm d}/r_{\rm co}$

$r_{\rm d} \lesssim r_{\rm co}$ — funnel-flow regime,

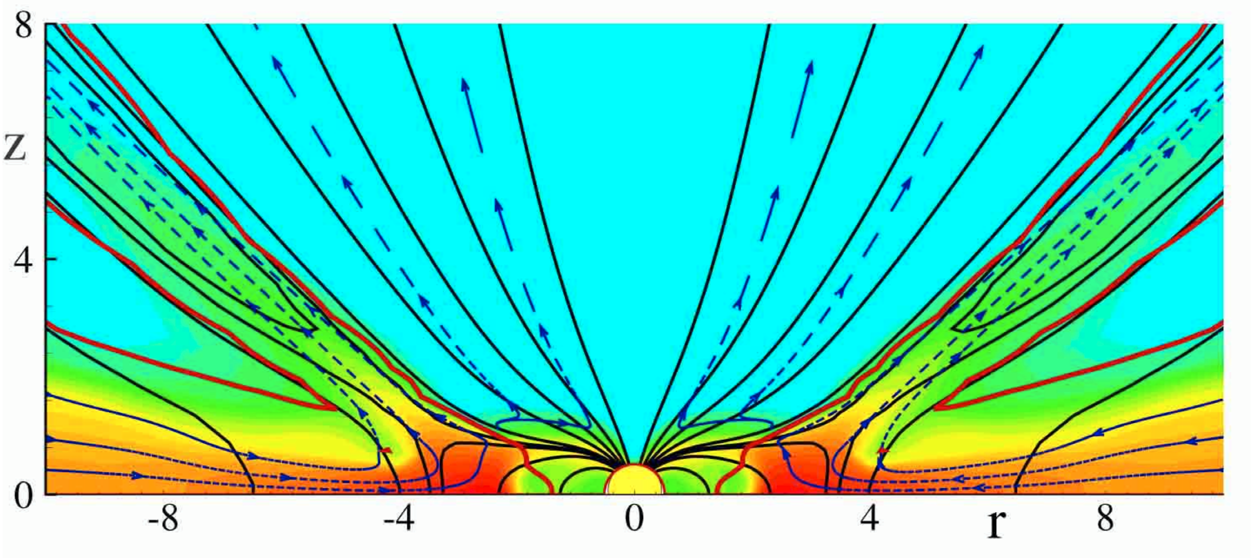
$r_{\rm d} \gtrsim r_{\rm co}$ — propeller regime.

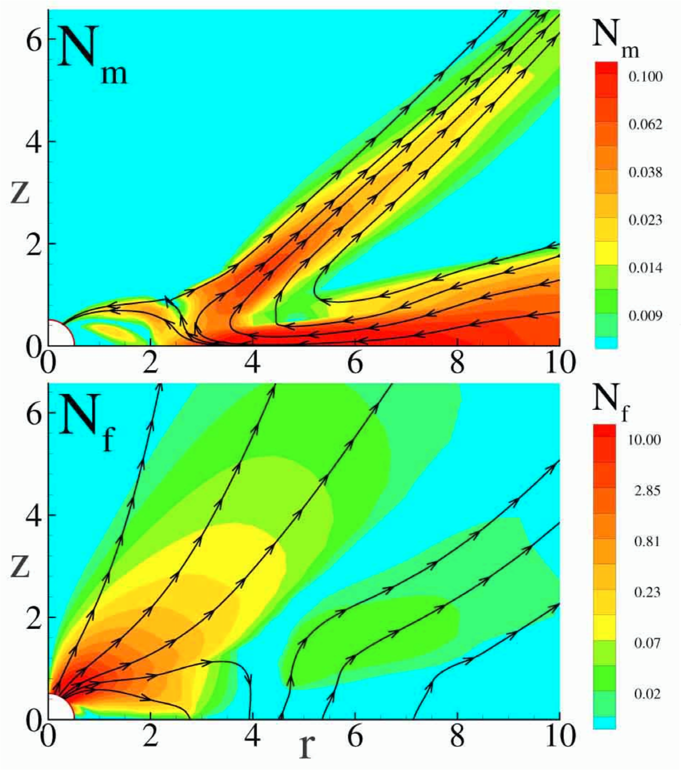
funnel-flow vs. propeller regimes

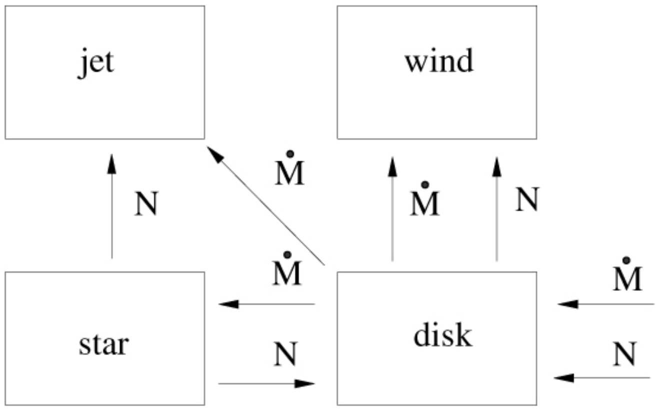


A “high” propeller state develops when the disk effective viscosity and magnetic diffusivity are relatively high. In this case most of the incoming matter is expelled from the system, both in the form of a wide-angle CDW from the inner regions of the disk and as a strong, collimated, magnetically dominated outflow along the open stellar field lines near the axis.

Propeller regime







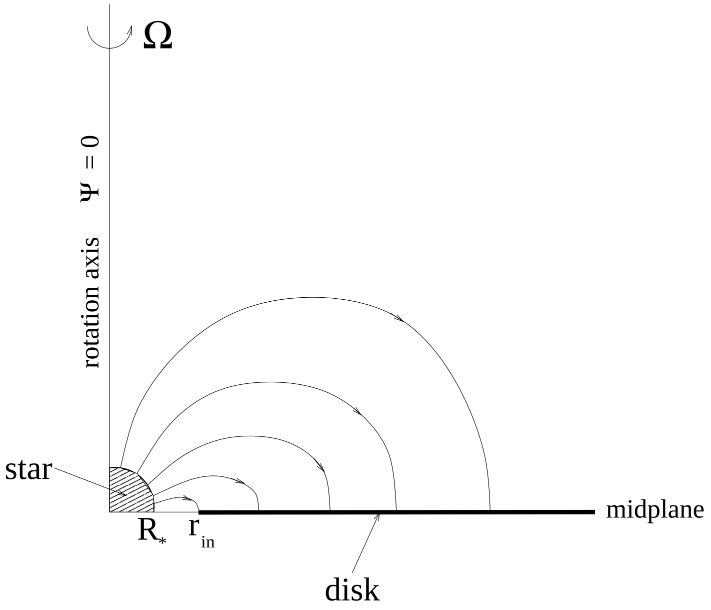
Romanova et al. (2005); Ustyugova et al. (2006).

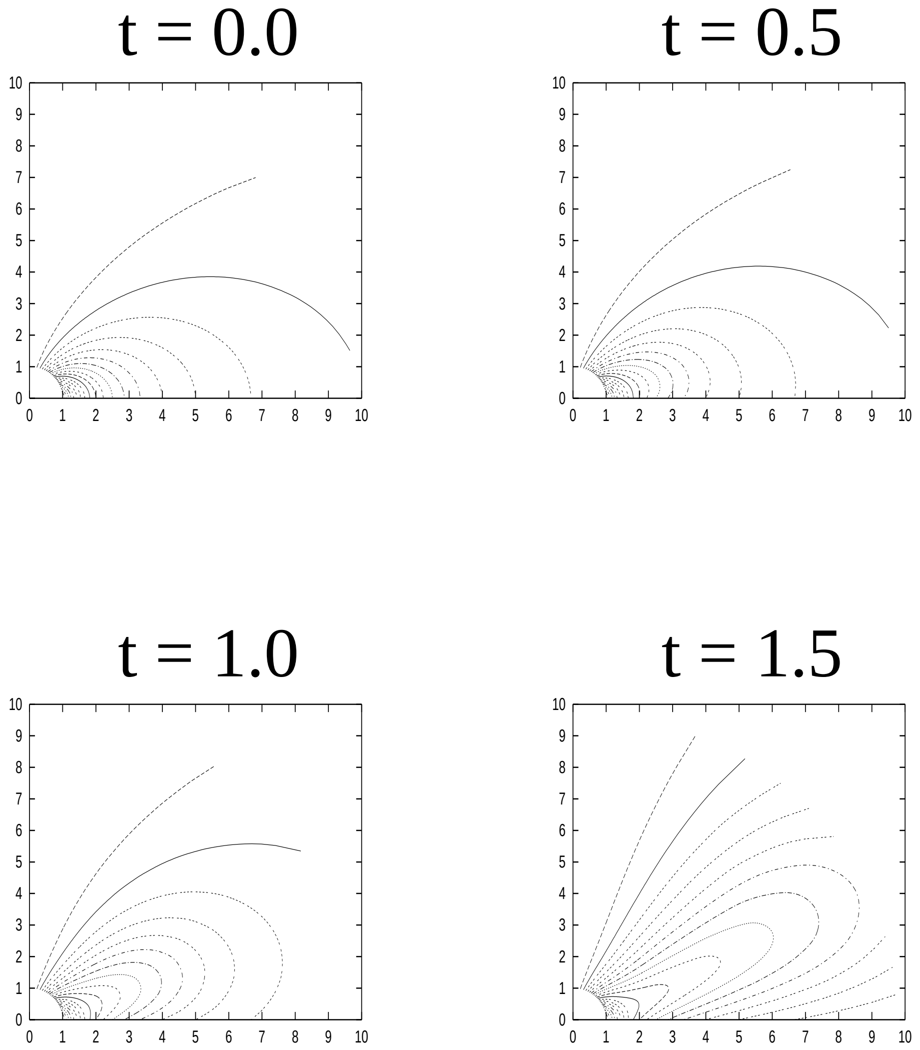
This mechanism could be relevant to the initial spindown (on a timescale $< 10^6$ yr) of CTTs.

Funnel-flow regime

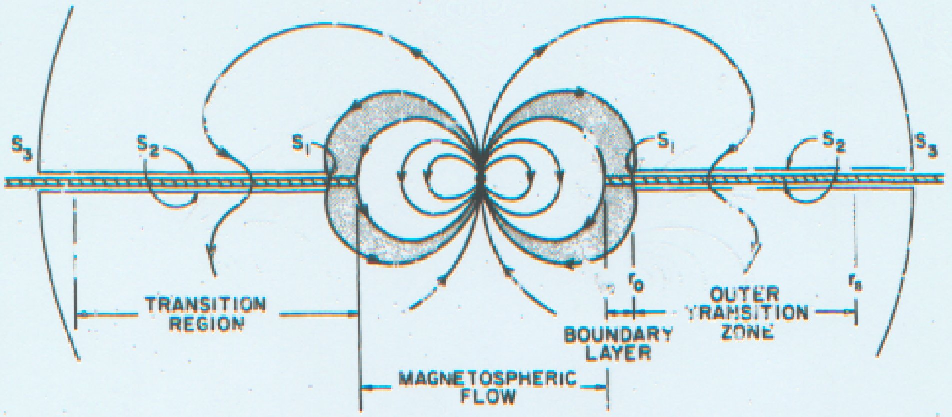
Ghosh & Lamb (1979; GL) proposed that a "disk locked" state in which the torque exerted by the field lines that thread the disk (as well as by the material that reaches the star) could keep the star rotating in equilibrium (neither spinning up nor down). This scenario could explain the relatively low rotation rates observed in CTTs (Königl 1991).

This picture was, however, challenged on various grounds. In particular, it was argued (Matt & Pudritz 2004, 2005) that the twisting of the magnetic field lines that thread the disk at $r > r_{\rm co}$ will tend to open them up, thereby reducing the spin-down torque on the star by more than an order of magnitude compared to the original calculation. Some previous models, in fact, postulated that the stellar field lines can effectively couple to the disk only in the vicinity of $r_{\rm co}$ (e.g., Shu et al. 2004).

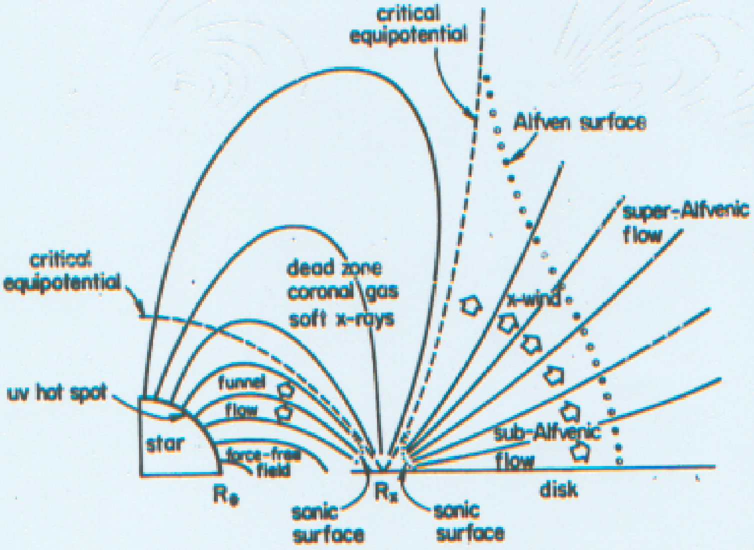




Uzdensky et al. (2002)



Ghosh & Lamb 1979



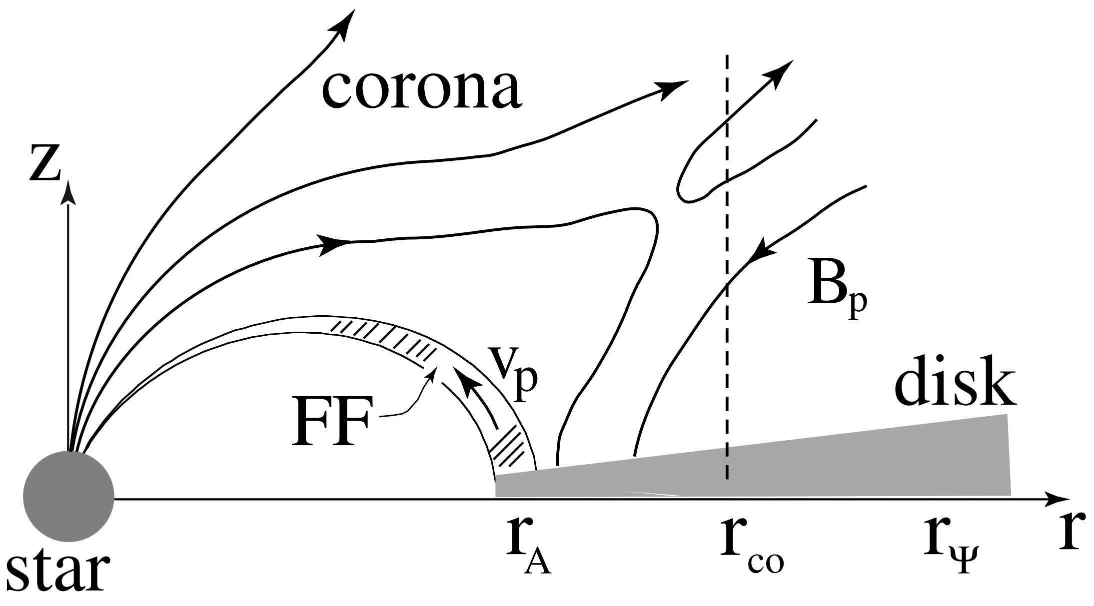
Shu et al. 1994

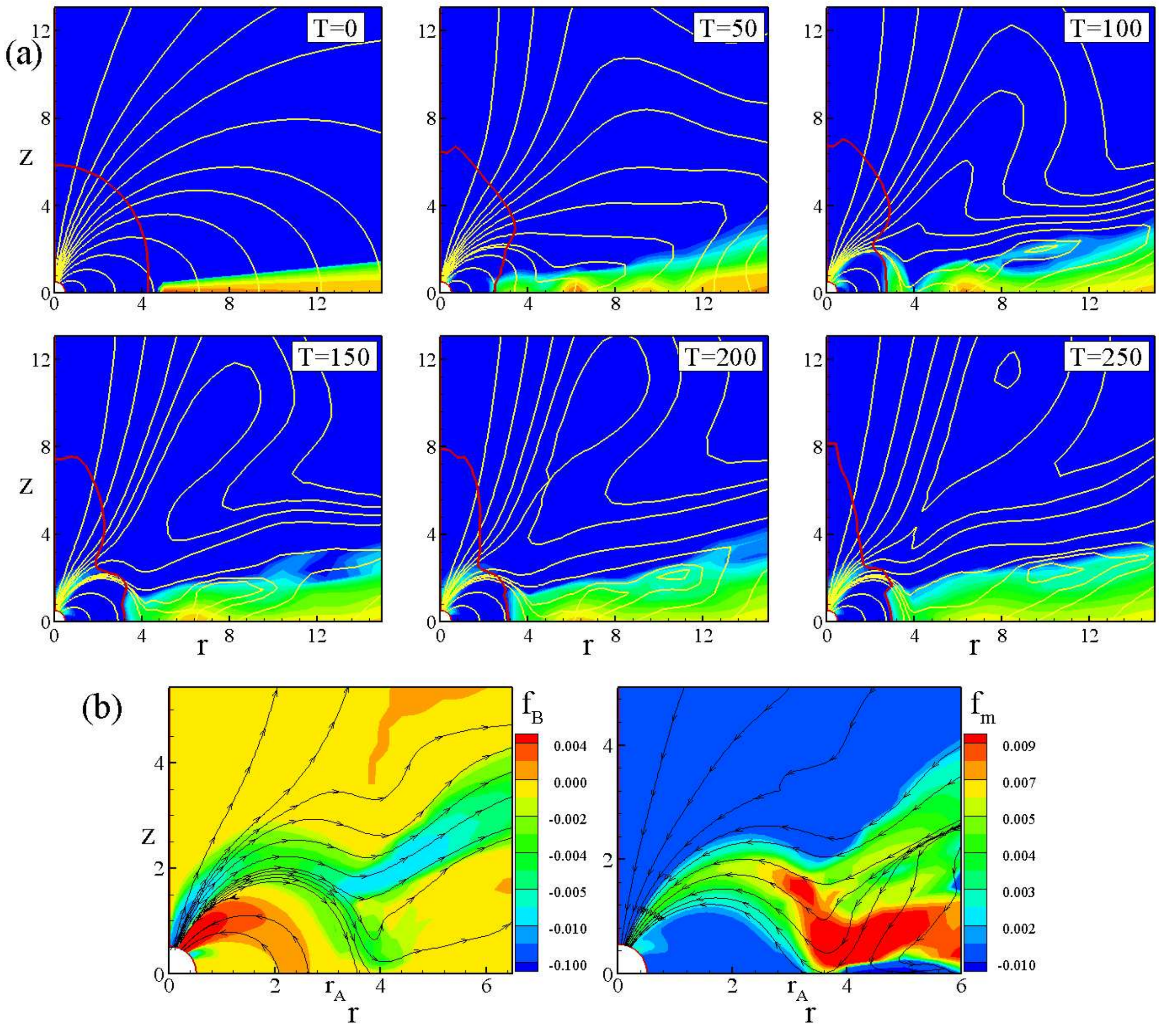
Extensive recent numerical simulations have, however, verified that, when the star has a strong enough field to disrupt the disk at a distance of a few stellar radii and channel accreting matter along field lines, it will become disk-locked and rotate with an angular velocity close to that of the disk at the truncation radius.

- It is found that $r_{\rm co}/r_{\rm d} \sim 1.2 - 1.5$ in equilibrium, very close to the prediction of the GL model.

- As envisioned by GL, closed magnetic field lines that link the star and the disk exert the dominant stresses in this interaction. However, in contrast to the original picture, this linkage does occur primarily near $r_{\rm co}$. The torque balance is achieved in part through field-line stretching (which mimics the connection to material at $r > r_{\rm co}$ in the GL model) and by magnetically driven outflows (which remain comparatively weak in the simulations).

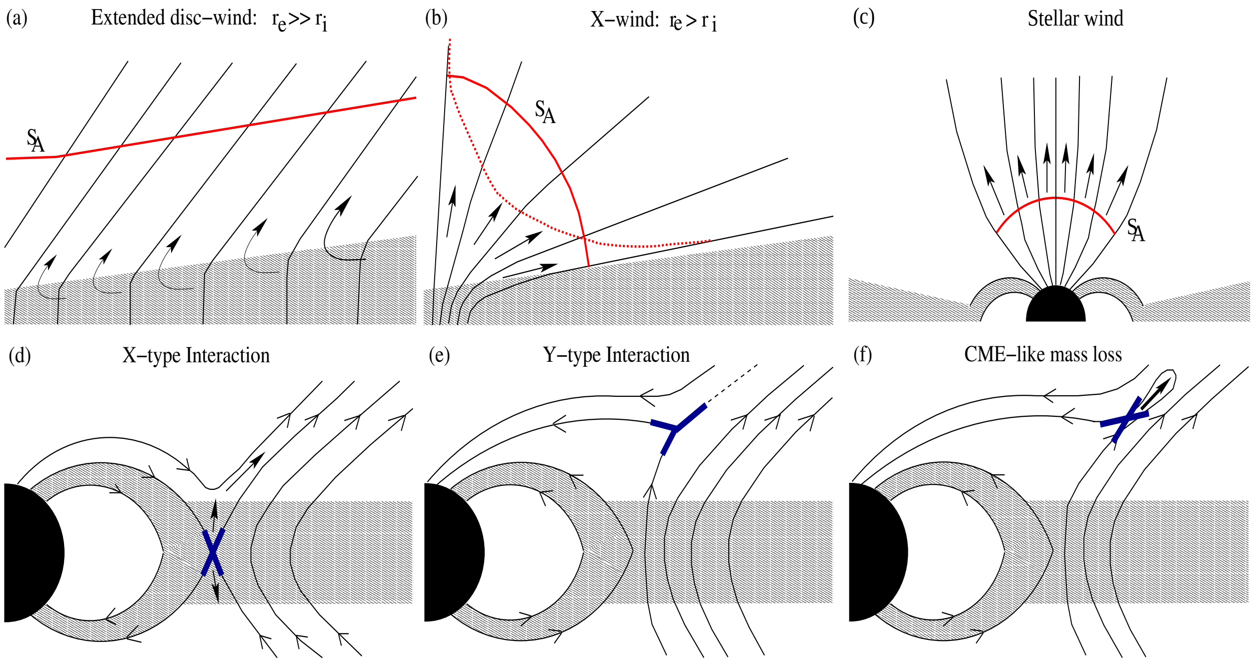
- Field-line opening is not a major impediment to this process, in part because opened field lines tend to reconnect (especially if the departure from axisymmetry is not large).





Long et al. (2005)

The field topology and the nature of the interaction could be modified if the disk itself contains a large-scale magnetic field (Hirose et al. 1997; Miller & Stone 2000; Ferreira et al. 2000, 2006; von Rekowski & Brandenburg 2004, 2006).

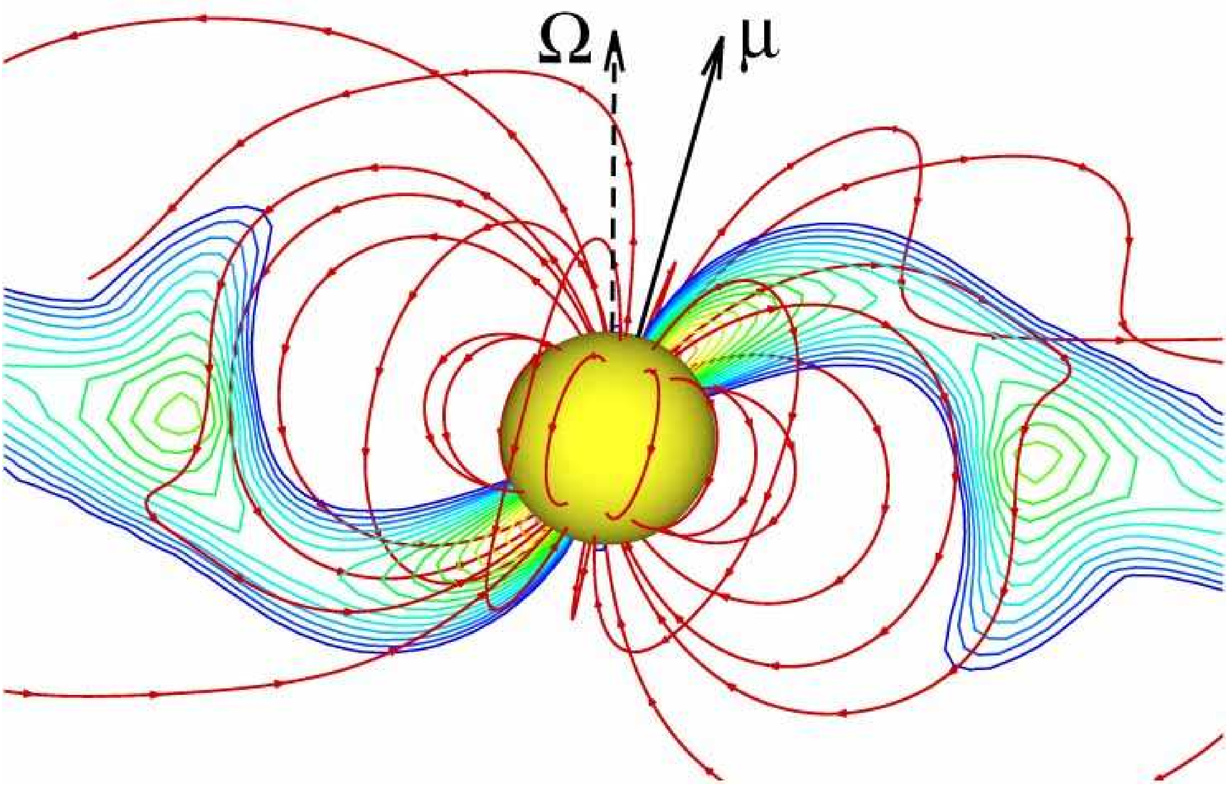


Ferreira et al. (2006)

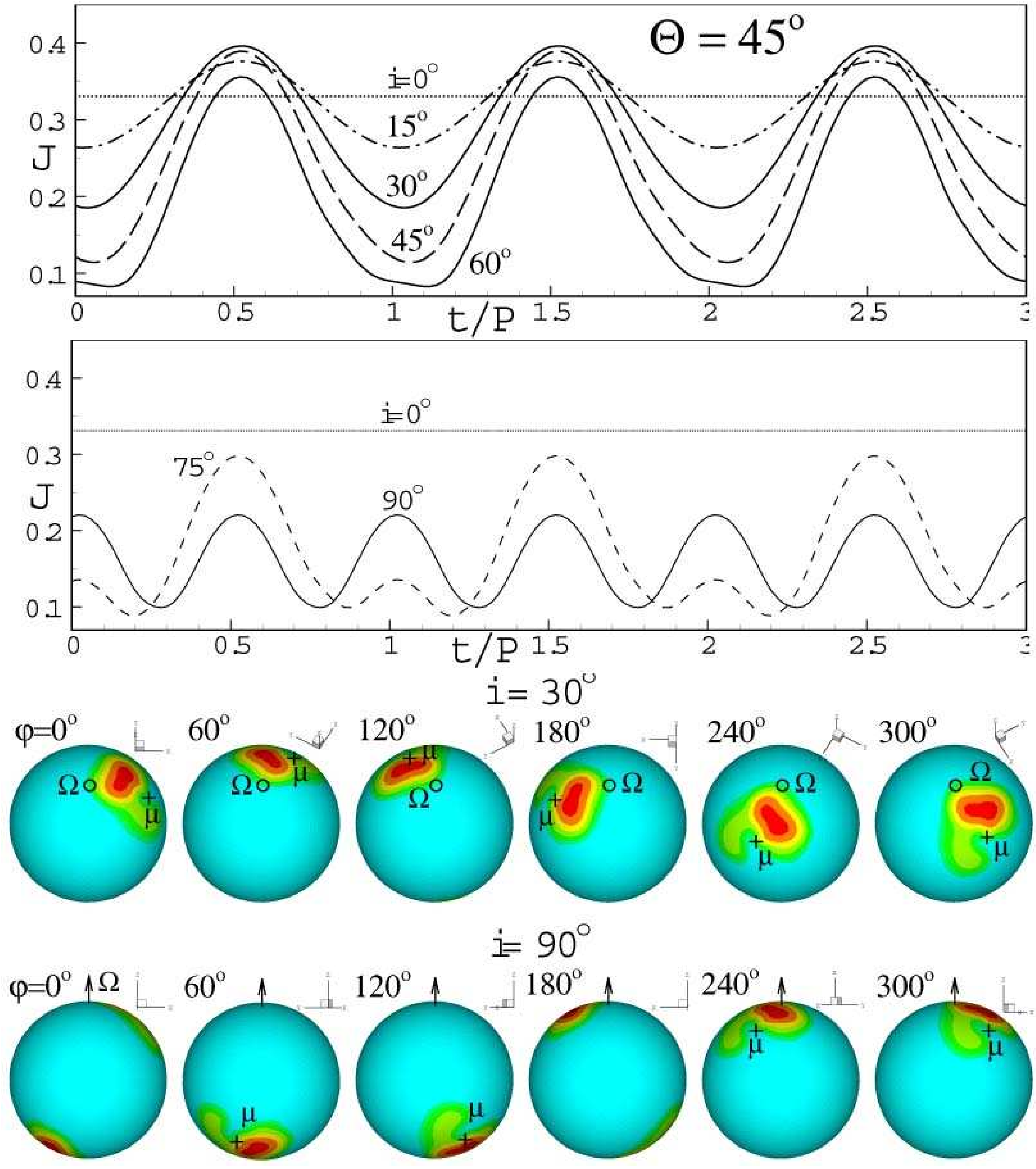
Nonsteady accretion

The magnetic interaction between stars and disks could be variable on timescales as short as Ω_*^{-1}.

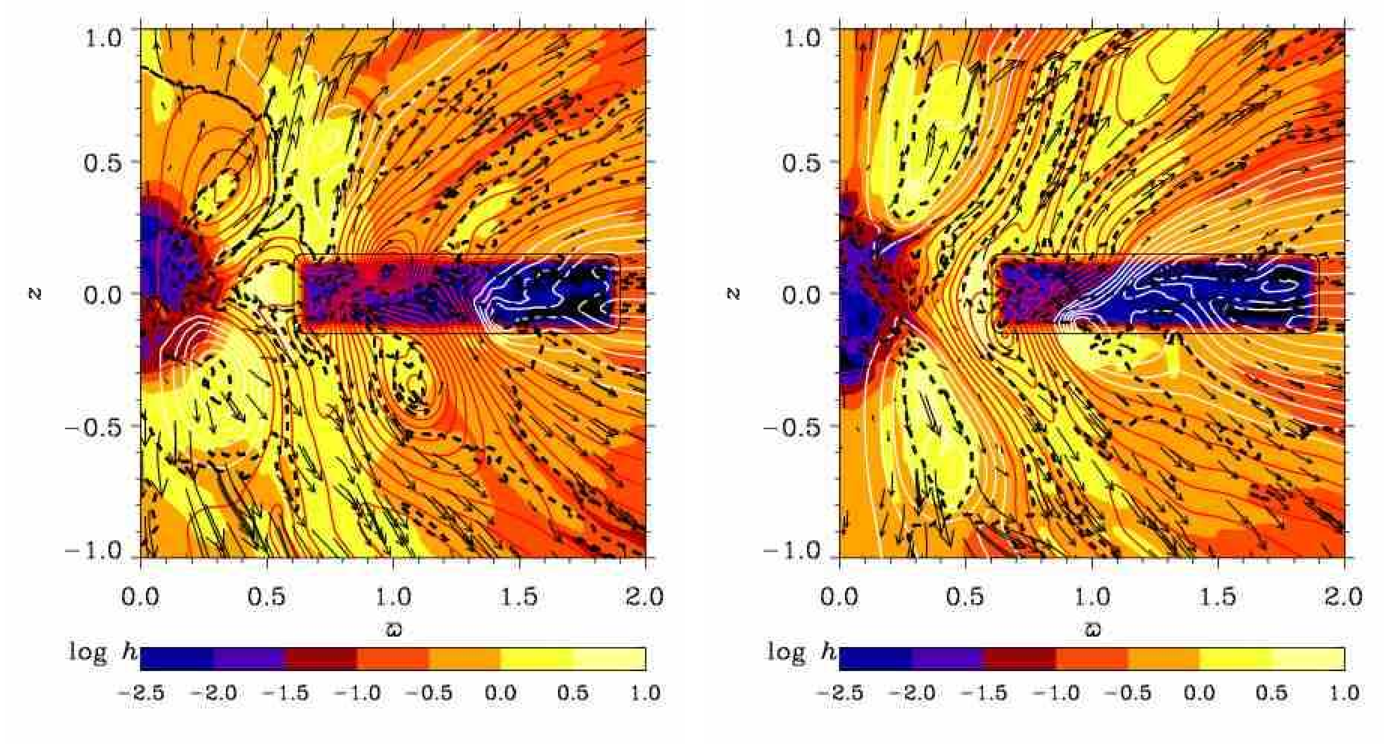
One possibility, which naturally gives rise to observed "hot spots," is for the system to lack axisymmetry (an inclined dipole, or a less ordered field topology)



It was also suggested (Goodson & Winglee 1999) that the truncation radius oscillates on the diffusion time scale of the field into the disk (resulting in field-line reconnection events and episodic polar ejections) if the diffusivity at the inner edge of the disk is relatively low ($|V_{\rm diff}/V_r| < 1$).



Romanova et al. (2004)



Magnetically connected (*left*, $t \approx 464$ days) and disconnected (*right*, $t \approx 469$ days) states in the star-and-disk dynamo model of von Rekowski & Brandenburg (2006).

In this model, the star–disk coupling is effected by the disk dynamo-generated magnetic field, and there are strong outflows, both from the inner disk and from the stellar surface. However, typically only a small fraction of the disk accretion flow reaches the stellar surface (and then only at low velocities; von Rekowski & Piskunov 2006).

Summary

- ♣ There is strong observational evidence for a disk–wind connection in YSOs. Magnetic fields have been implicated theoretically as the most likely driving mechanism of the observed winds and jets.
  - The ubiquity of the outflows may be related to the fact that centrifugally driven winds (CDWs) are a potentially efficient means of transporting angular momentum from the disk. Recent observations, interpreted in terms of YSO jet rotation, are consistent with this notion, but this interpretation is still being debated.
- ♣ Ordered magnetic fields could arise in YSO disks on account of (i) advection of interstellar field by the accretion flow, (ii) dynamo action in the disk, and (iii) interaction with the stellar magnetic field.
- ♣ Semianalytic MHD models have been able to account for the basic structure of diffusive disks that drive CDWs from their surfaces as well as for the formation of such systems in the collapse of rotating molecular cloud cores.

These studies are being advanced by increasingly more elaborate numerical simulations (2D/3D, ideal/nonideal MHD) that are in a unique position to examine the global properties, time evolution, and dynamical stability of the disks.

  - Realistic disk ionization structure and conductivity are already being incorporated into the models, including the interplay between gas and dust dynamics.
  - Models that combine vertical (through magnetic braking or a CDW) and radial (through MRI-induced turbulence) magnetic angular momentum transport have also already made a debut.

- Robust observational evidence also exists for a magnetic interaction between CTT disks and their respective YSOs, including strong indications of field-channeled flows onto the stellar surfaces. Theoretical progress is somewhat hampered, however, by the fact that the magnetic field topology in the interaction region is still not well understood.
  - Owing to the complexity of this problem, MHD numerical simulations have become an indispensable tool in these studies.