

Magnetic Braking of Accreting T Tauri Stars: Effects of Mass Accretion Rate, Rotation, and Dipolar Field Strength

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1. Introduction

- Classical T Tauri stars undergo gravitational contraction, and observations suggest they actively accrete from disks^[1,2,3]. However, observations also suggest $\sim \text{const.}$ spin distributions over $\sim \text{Myr}$ ^[4,5,6]; many rotate \ll break-up velocity^[4,6].

How does the star remove angular momentum (AM) during its PMS phase?

- Rotational evolution of accreting PMS stars is theorized to be influenced by magnetic interaction with its accretion disk^[7,8].
- We simulate 2.5D MHD, axisymmetric star-disk interaction (SDI)—with an initial dipolar field and a viscous/resistive accretion disk—and investigate how the following parameters affect the net stellar torque:
 - Stellar magnetic field strength B_\star ;
 - Mass accretion rate \dot{M}_{acc} (via initial disk density $\rho_{\text{d},\star}$);
 - Stellar break-up fraction f .
- We fit semi-analytic functions to predict the net stellar torque for our regime, as well as the possibility of investigating spin evolution using 1D stellar evolution codes.

2. Stellar Torque Contributions

3 mechanisms exchange AM with star (Fig 1):

Region (1): Stellar Wind

- Ejected along open field lines anchored to the star \rightarrow **spin-down**

Region (2): Magnetospheric Ejections (MEs)

- Star-disk differential rotation “twists” field \rightarrow periodic inflation and reconnection events.
- MEs extract disk AM, reducing disk velocity Ω_{disk} . Some is ejected out the domain, but some is exchanged with star.
- Sub-Keplerian disk has lower differential rotation, so $\Omega_{\text{disk}} = \Omega_\star$ at $R_{\text{co,m}}$ ($< R_{\text{co}}$ - the Keplerian corotation radius), where Ω_\star is the stellar rotation rate.
 - $R_t \leq R_{\text{co,m}}$: $\Omega_{\text{disk}} > \Omega_\star \rightarrow$ **spin-up**
 - $R_t \geq R_{\text{co,m}}$: $\Omega_{\text{disk}} < \Omega_\star \rightarrow$ **spin-down**

Region (3): Accretion

- Disk truncates at R_t , where disk/magnetic pressure balance - adds angular momentum onto star \rightarrow **spin-up torque**.

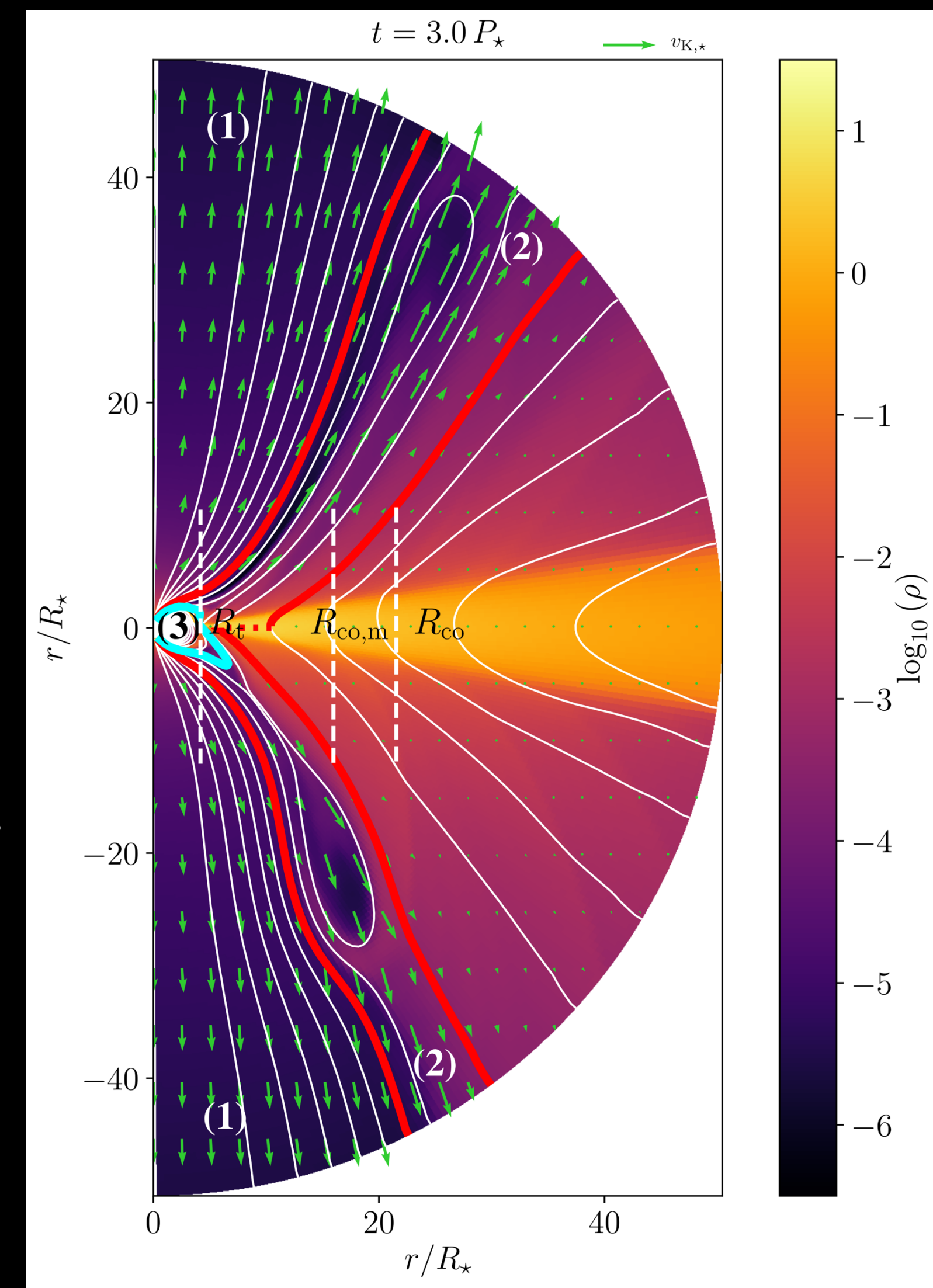


Figure 1: Snapshot density colormap for SDI domain.

3. Parameter Regime

Stellar magnetic field strength $B_\star \approx 0.5 - 2$ kG:

- $\downarrow B_\star \rightarrow \downarrow R_t$ (decreased magnetic pressure) (Fig 2b)

Mass accretion rate $\dot{M}_{\text{acc}} \approx 10^{-9} - 10^{-8} M_\odot \text{ yr}^{-1}$:

- $\uparrow \dot{M}_{\text{acc}} \rightarrow \downarrow R_t$ (increased disk pressure) (Fig 2c)

Stellar break-up fraction $f = 0.001 - 0.0625$:

- $\uparrow f \rightarrow \downarrow R_t$ (decreased star-disk differential rotation/twist \rightarrow decreased magnetic pressure) (Fig 2d)

Smaller $R_t \rightarrow$ field lines connect at lower latitudes, opening up larger area on the star for wind ejection (Fig 2 zoom panels).

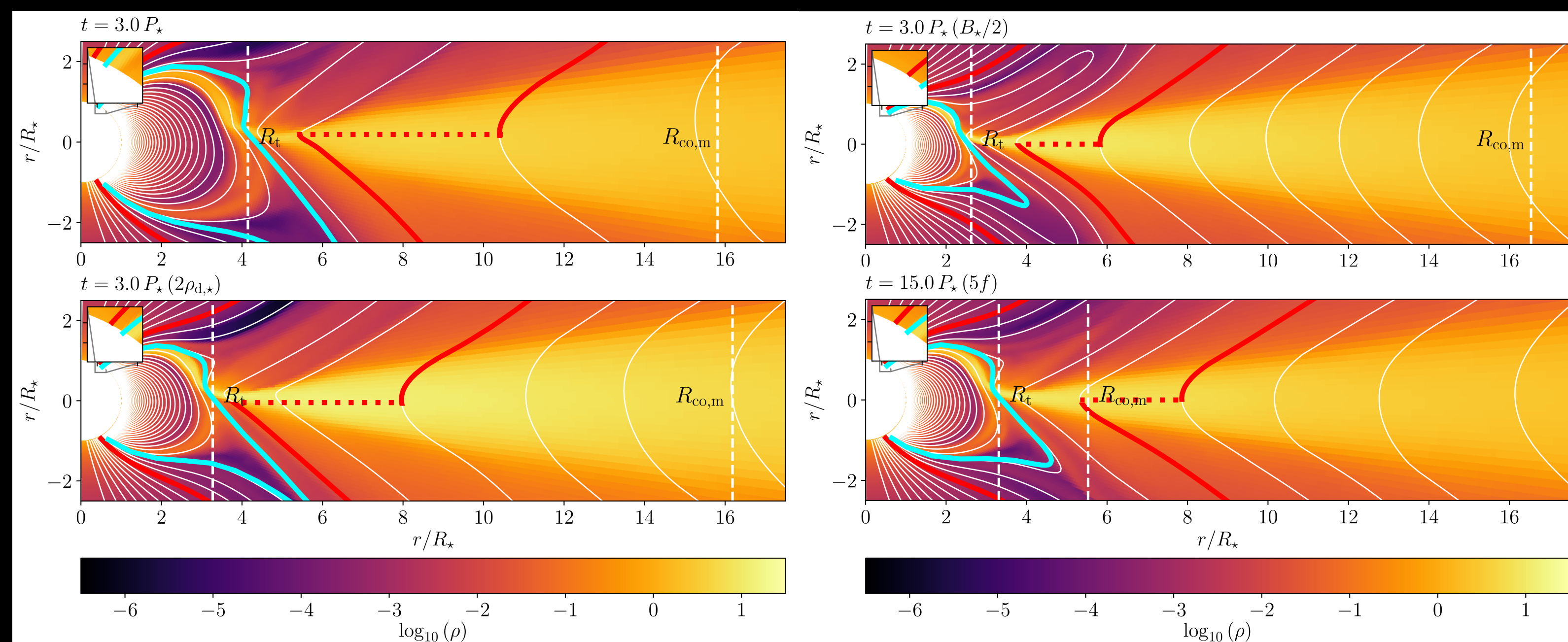


Figure 2: (a) Representative model, (b) $B_\star/2$ model, (c) $2\rho_{\text{d},\star}$ model, (d) $5f$ model.

4. SDI Net Torque Formulation

$$\dot{J}_\star = \dot{J}_{\text{acc}} + \dot{J}_{\text{ME},\star} + \dot{J}_{\text{wind}}$$

Accretion

$$\dot{J}_{\text{acc}} = \dot{M}_{\text{acc}} \Omega(R_t) R_t^2$$

Sub-Keplerian disk, due to MEs, reduces accretion torque relative to Keplerian solution:

$$\Omega(R_t) \approx 0.64 \Omega_{\text{Kep}}(R_t) \quad (\text{ignoring small } R_t \text{ dependence}).$$

R_t can be parameterized as the ratio of the accretion flow's magnetic and kinetic energies, i.e.,

$$\frac{R_t}{R_\star} \sim \left(\frac{B_\star^2}{\dot{M}_{\text{acc}}} \right)^{0.34}$$

Steeper scaling than analytical case ($2/7 \approx 0.286$), as accretion disk perturbs the magnetosphere.

MEs

The ME torque scales with the star-disk differential rotation, poloidal field strength, and R_t :

$$\dot{J}_{\text{ME},\star} \propto \left[\left(\frac{R_t}{R_{\text{co,m}}} \right)^{3/2} - 1 \right] B_\star^2 R_\star^3 \left(\frac{R_t}{R_\star} \right)^{-2.54}$$

Stellar Wind

$$\dot{J}_{\text{wind}} = \dot{M}_{\text{wind}} \Omega_\star \langle r_A \rangle^2$$

where \dot{M}_{wind} is the mass loss rate and $\langle r_A \rangle$ is the Alfvén radius, i.e., the “effective magnetic lever arm”. $\langle r_A \rangle$ can be parameterized as the ratio of the wind's magnetic and kinetic energies, i.e.,

$$\frac{\langle r_A \rangle}{R_\star} \sim \left(\frac{\Phi_{\text{wind}}^2}{\dot{M}_{\text{wind}}} \right)^{0.373}$$

where Φ_{wind} is the open magnetic flux. (neglecting wind centrifugal correction term for rapidly rotating cases).

When $\dot{M}_{\text{wind}} \ll \dot{M}_{\text{acc}}$, open flux increases with \dot{M}_{acc} (decreases with R_t): where Φ_\star is the total stellar magnetic flux.

$$\frac{\Phi_{\text{wind}}}{\Phi_\star} \sim \left(\frac{R_t}{R_\star} \right)^{-1.34} \quad (\text{ignoring small } f \text{ dependence}).$$

SDI geometry opens up larger area for stellar wind ejection \rightarrow **increases open flux**, compared to isolated wind simulations (where Φ_{wind} largely determined by \dot{M}_{wind}).

4. Conclusions

- All our simulations are **net spin-up**.
- MEs appear to reduce the efficiency of the accretion torque**, but in our parameter regime, the **MEs also spin up the star further**.
- Accretion disks appear to increase the efficiency of the stellar wind torque** (when $\dot{M}_{\text{wind}} \ll \dot{M}_{\text{acc}}$), because **SDI opens more of the stellar magnetic flux**, compared to isolated wind simulations, resulting in increased **spin-down torque**.
- A net **spin-down** regime could be achieved by:
 - Entering the “propeller” regime, where accretion is inhibited (by increasing B_\star or decreasing \dot{M}_{acc}), and where MEs could provide a **spin-down torque** (currently being explored in new parameter study).
 - More massive stellar winds (higher coronal T).
 - 3D simulations/more realistic magnetic topologies.

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