Stellar wind torques in T Tauri stars: How to prevent spin-up?

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Abstract

Classical T Tauri stars (CTTs) are young stellar objects (a few Myr old), which magnetically interact with their surrounding disks. This interaction controls their rotational evolution. Due to both accretion and contraction, these pre-main-sequence stars are expected to spin up. However, observations show that CTTs maintain a constant rotation in time, indicative of angular-momentum-loss processes that prevent their stellar spin rates to increase due to both accretion and contraction. Various types of outflows (e.g., magnetized stellar winds, magnetospheric ejections, disk winds) have been proposed to explain this phenomenon. In this poster, we present numerical simulations that quantify the magnetic braking (due to stellar winds) in accreting stars. We find that stellar winds originated from CTTs brake the stellar rotation more efficiently than outflows from diskless stars. However, we predict that these winds should eject at >10% of the mass-accretion rate in order to counteract the stellar spin-up due to accretion.

1. Definitions

R_* = stellar radius.
ρ_* = stellar surface density.
B_* = surface magnetic field strength, equator.
Ω_* = stellar angular rotation rate of star.
P_* = stellar rotation period
υ_{esc} = escape speed from stellar surface.
$\dot{M}_{sw}$ = stellar wind mass outflow rate.
$\langle r_A \rangle$ = stellar-wind effective Alfvén radius.
τ_{sw} = stellar-wind torque.
$\dot{M}_{acc}$ = mass accretion rate.
τ_{acc} = angular momentum accretion rate.
Φ_{open} = stellar-wind open flux

$$Y_{open} \equiv \frac{\Phi_{open}^2}{4\pi R_*^2 \dot{M}_{sw} \upsilon_{esc}}$$

2. Simulation Method & Parameter Study

Method: We employ 2.5D axisymmetric, MHD, and time-dependent simulations computed with the PLUTO code (Mignone et al. 2007). Two different systems are considered: isolated (i.e., weak-line T Tauri and main-sequence) and accreting (i.e., classical T Tauri) stars. For the classical T Tauri stars simulations the disk is taken to be Keplerian, viscous, and resistive, modeled with an alpha parametrization (Shakura & Sunyaev 1973). The stellar wind is thermally driven in both systems.

Parameter Study: We obtained 10 MHD numerical solutions in total divided into two sets. The first grid includes five cases and corresponds to isolated-stellar-wind (ISW hereafter) simulations (i.e., isolated stars). The second grid has five star-disk-interaction (SDI hereafter) cases (i.e., accreting stars). For both grids the only parameter varied is the stellar magnetic strength.

Fixed Parameters: The stellar spin rate is fixed at 5% of the stellar break-up speed. The stellar-surface mass density and coronal temperature are also fixed throughout the study. The stellar magnetosphere has a dipolar geometry. Finally, in the SDI cases, we fix the initial disk surface density and the disk alpha parameter.

Varied Parameters: We completed a parametric study in the dipolar magnetic field strength, B_*, which is defined at the stellar equator. B_0 is 0.1 kG.

- **ISW simulations:** B_* = 0.8, 1.6, 3.25, 6.5, and 13 B_0
- **SDI simulations:** B_* = 1.6, 3.25, 6.5, 9.75, and 13 B_0

3. The Two Types of Open Stellar Magnetospheres

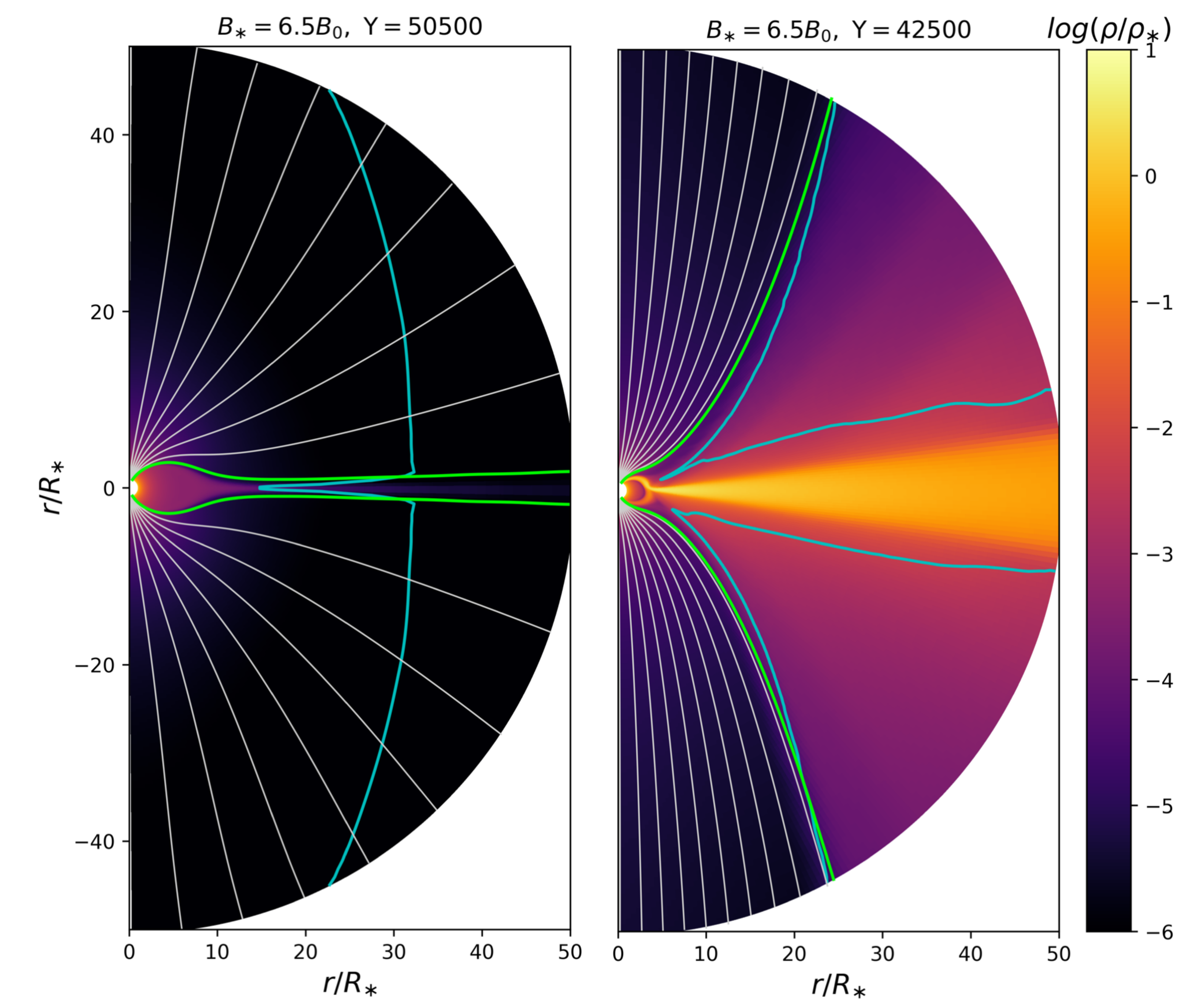

Figure 1: *Colorscales of logarithmic normalized density of the two systems, ISW (left) and SDI (right), studied in this work. Each plot includes magnetic field lines (white lines), which carry a stellar wind. In both panels, the green lines determine the boundaries of the stellar-wind flux tube. The cyan lines show the Alfvén surafce of the two simulations. An isolated stellar wind (left panel) opens the stellar magnetosphere and fills with plasma the entire domain. A stellar wind from SDI systems (right panel) is confined due to the presence of magnetospheric ejections (e.g., Bouvier et al. 2003, Zanni & Ferreira 2013) and therefore, propagates within an hourglass-shaped flux tube. This feature results in a slower flow acceleration and a lower wind speed at the Alfvén surface.*

4. Stellar-Wind Torque Laws in SDI systems

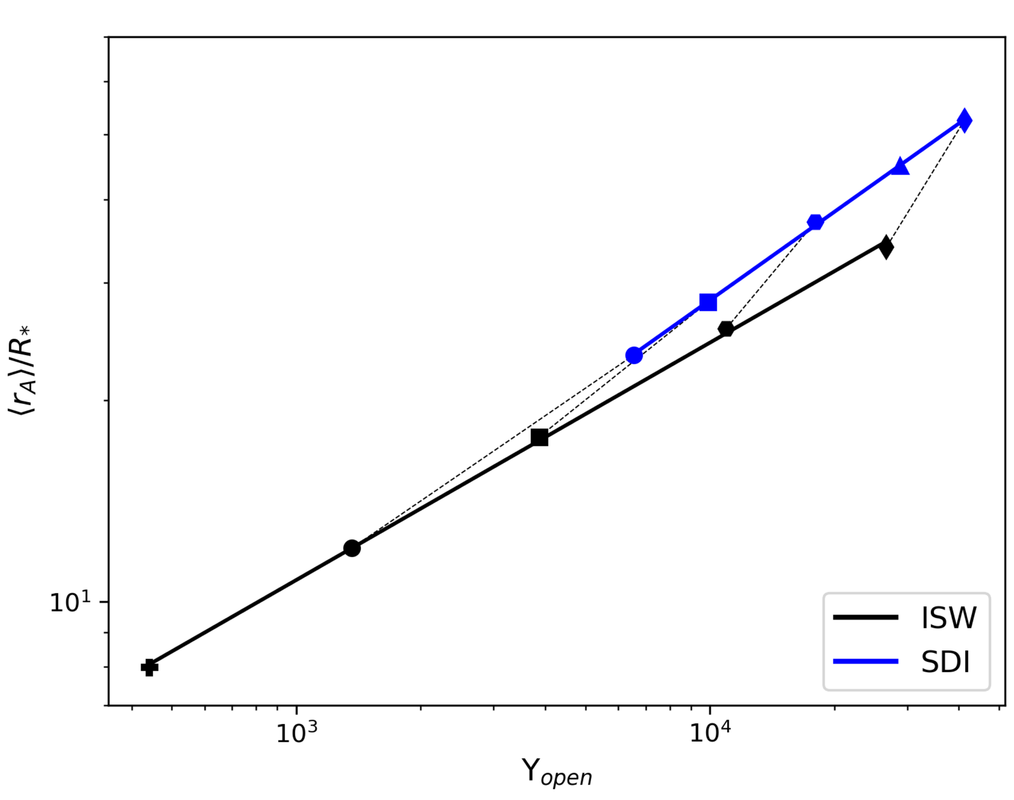

Figure 2: *Normalized Alfvén radius vs. parameter Y_{open} for all the cases of this work. Each point in the figure corresponds to a single simulation. The blue and black colored data points/fits denote star-disk-interaction (labelled as "SDI") and isolated-stellar-wind simulations (labelled as "ISW"), respectively. Data points of the same symbol are connected with dashed lines to show numerical solutions having the same surface magnetic field strength. Figure from Pantolmos et al. 2020.*

The spin down torque due to a magnetized wind is

$$\boldsymbol{\tau_{sw} = \dot{M}_{sw} \Omega_* R_*^2 \left(\frac{\langle r_A \rangle}{R_*}\right)^2},$$

where $<r_A>$ is the effective or averaged Alfvén radius of the flow, which brakes the stellar rotation. In figure 2, the following semi-analytic function is used to fit the data

$$\boldsymbol{\frac{\langle r_A \rangle}{R_*} = K_o Y_{open}^{m_o}},$$

where parameter Y_{open} is the wind magnetization (see e.g., Matt & Pudritz 2008, Réville et al. 2015, and section 1). K_o, m_o are dimensionless fitting constants. We get

- **ISW:** $K_o = 0.927$, $m_o = 0.355$
- **SDI:** $K_o = 0.495$, $m_o = 0.439$

For a given value of Y_{open}, the stellar wind from a SDI system has a larger lever arm and therefore, exerts a stronger torque on the star. This is a consequence of the outflow having more open magnetic flux and a slower acceleration (Pantolmos et al. 2020).

Combining the previous two equations, we derive a predictive formula for torques due to magnetized stellar winds in SDI systems (i.e., the CTTs phase of stellar evolution)

$$\boldsymbol{\dot{J}_{sw} = K_o^2 (4\pi)^{-2m_o} \Omega_* \upsilon_{esc}^{-2m_o} R_*^{2-4m_o} \dot{M}_{sw}^{1-2m_o} \Phi_{open}^{4m_o}}.$$

5. Global Properties of SDI Simulations

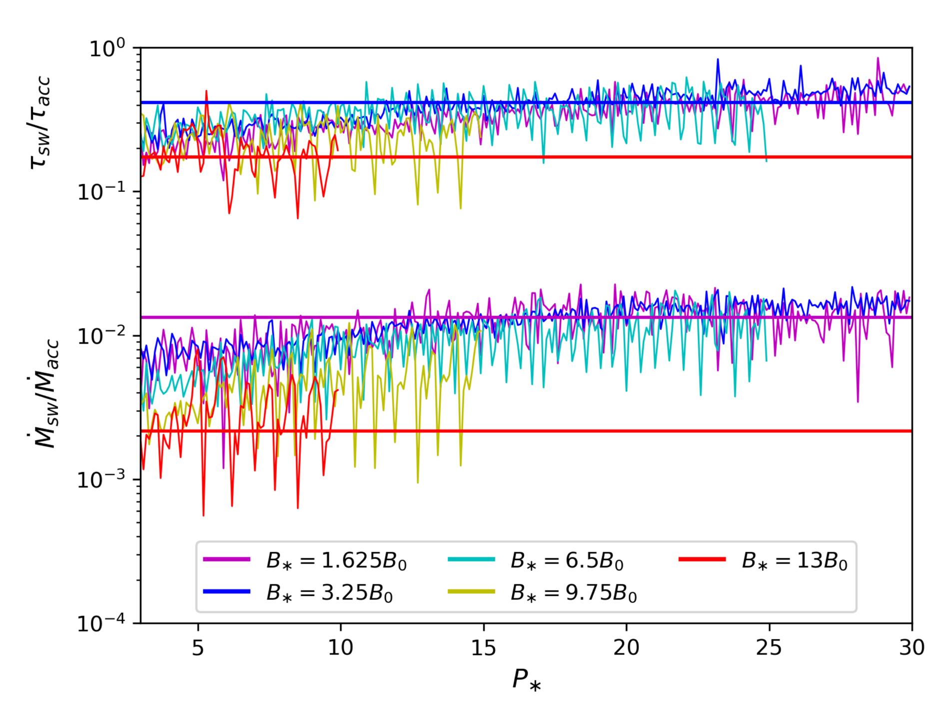

Figure 3: *Stellar-wind efficiency ratios, $\frac{\dot{M}_{sw}}{\dot{M}_{acc}}$ and $\frac{\tau_{sw}}{\tau_{acc}}$ as functions of time (expressed in terms of stellar rotation periods), for all the SDI solutions in this study. The straight lines show the time-averaged values of these two quantities. Figure from Pantolmos et al. 2020.*

- In this study , the mass accretion rate, $\dot{M}_{acc}$, varies from 4×10^{-9} to 10^{-8} solar masses per year.
- In all the SDI cases the star experiences a spin-up net torque.
- Despite the increased torque efficiency, a stellar wind should eject at > 10% of the mass accretion rate in order to at least balance the spin-up torque due to accretion (in this estimate the stellar contraction is not considered).
- For example, using BP Tau as a representative CTTs case, Ireland et al. (2020) predicts $\frac{\dot{M}_{sw}}{\dot{M}_{acc}} \approx 25\%$ in order to achieve $\tau_{sw} = \tau_{acc}$.

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SPIDI webpage: spidi-eu.org